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Research article

Performance evaluation of a PV panel incorporating active cooling technique for efficiency enhancement in hot climatic conditions of Kalaburagi city

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Abstract: One of the major parameters influencing Photovoltaic (PV) panel's efficiency is temperature. The main problem identified in this study is that high surface temperatures cause PV panels to operate less efficiently and shortens their lifetime. Consequently, a cooling system is needed that diminishes panel temperature and enriches its efficiency. The main objective of the proposed research is to investigate the efficacy of an active cooling system that uses a copper-tube thermal collector integrated with a radiator-style heat exchanger to improve the performance of the PV panel. The city of Kalaburagi in the Indian state of Karnataka was chosen for the experimental testing because of its hot temperature. Our findings showed that the proposed active rear surface cooling system successfully reduced surface temperature by 16 °C on average. Cooled and uncooled PV panels had 23.35% and 21.75% average electrical efficiency, respectively. Cooling increased efficiency by 1.6%. The PV system's average thermal efficiency with cooling was 59.6%, and the combined total efficiency reached 82.95%. Thus, our findings presented in this research demonstrate how effective the suggested active back surface cooling was in relation to Kalaburagi city's climate. The research also showed that a closed-loop water circulation system improves PV module performance.

Keywords: active cooling technique; closed-loop water circulation system; copper tube thermal collector; electrical efficiency; photovoltaic panel; radiator style heat exchanger; thermal efficiency

1. Introduction

In light of the global situation, it is essential to reduce emissions of greenhouse gases and fight against climate change; utilizing solar power greatly helps these goals. Additionally, it reduces the use of energy sources that are not renewable [1]. The benefits of solar energy are indisputable, and its ability to generate power in a sustainable manner contributes to its widespread use. Numerous nations rely heavily on solar energy to help them achieve their ambitious clean energy targets [2].

Solar photovoltaic technology to a greater extent is appealing compared to diverse renewable energy sources owing to its greater geographic accessibility and economic viability [3]. It is imperative to conduct an on-going and thorough analysis of photovoltaic technology's real energy performance, since it is a potential pivotal energy source for sustainable growth in the future. A comprehensive analysis of the ways in which external factors impact solar panel efficiency is necessary as the world moves toward more sustainable energy sources [4].

Many environmental conditions affect how well photovoltaic panels work. These include parameters like temperature, solar irradiance, wind velocity, rainfall, dust, humidity, and cloud coverage [5]. Temperature is crucial among these since it affects how well PV panels function as a whole [6]. High operating temperatures drastically affect effectiveness and output power of PV panels. Elevated temperatures put stress on a solar panel's constituent materials, speeding up their physical and chemical deterioration. Additionally, long-term exposure to high temperatures can result in considerable thermal stress, which shortens the panel's lifespan and accelerates disintegration [7,8]. Improving effectiveness and electrical power production of the PV panel is as simple as lowering the temperature at which it operates [9].

Through the development of a prototype PV panel that utilizes a water-cooling chamber with the intention of cooling it, at the back side, Ilaf N. Rasool *et al.* [10] examined the performance and power production efficacy of the panel . The solar panel cooling assembly was a closed cycle system in which the cooling water is supplied at varying flow rates to the panel directly via the back side. Findings demonstrated that using mass flow rates of 1.5, 2, 2.5, 3, and 3.5 L/min enhanced electrical efficiency by 10.42%, 11.87%, 13.77%, 18.1%, and 19.72%, respectively. Thermal efficiency noted were 49.7% and 79.2% at 1.5 and 3.5 L/min, respectively. In an experimental investigation, Talib K. Murtadha *et al.* [11] used water and aluminum-oxide nanofluid at different concentrations (1 weight percent, 2 weight percent, and 3 weight percent) to cool monocrystalline PV panels. The cooling fluid flow rates used in the study ranged from 0.8 to 1.6 L/min. Compared to an uncooled panel, when using nanofluid with a 3 weight percent concentration to cool the panel, energy yield enhanced by 13%. Krzysztof Sornek *et al.* [12] suggested a special water cooling solution for PV panels. Two monocrystalline solar panels, one rated at 50 W and the other at 310 W, were tested in a laboratory setting as well as in real-world operation to inspect the cooling system's performance. Contrasting the 310 W water-cooled panel in this system to an uncooled panel, the greatest temperature difference was about 24 K. When the temperature of the cells was reduced, the water-cooled solar panel yielded 10% additional power in contrast to the uncooled one. Uzair Nasir *et al.* [13] Investigated how cooling affects the efficiency of photovoltaic modules, both polycrystalline and monocrystalline, through an experimental analysis. A model of water cooling pipe on the rear was utilized in experiment. An elliptical copper pipe heat exchanger was thermally attached to solar panels' backside. Utilizing a 0.052 L/sec mass flow rate, water was employed as a cooling fluid. Findings showed that polycrystalline PV module may boost effectiveness by 3.45% and a monocrystalline PV module by 4.46%. Three PV modules, PV_1 with no cooling, PV_2 with a fin structure, and PV_3 with both a fin structure and spray cooling, were experimentally investigated by Omar Rashid Ismael and Selcuk Selimli [14]. The findings demonstrated that PV_2 and PV_3 modules have lower temperatures than the PV_1 module by 1.59% and 4.59%, respectively. The PV_2 and PV_3 modules outperformed the PV_1 module in terms of energy efficiency, with 1.40 and 2.20%, respectively, and exergy efficiency, with 3% and 6.61%, respectively. Ahmed Ameen Ali *et al.* [15] conducted research utilizing experimental techniques to lower the operating temperatures of photovoltaic panel. A Bare PV system, a PV/W system cooled by a dushing method, and a third PV/SW system covered by a new sawdust back layer were all tested under standard conditions. According to the surface temperature analysis, the new PV/SW system achieved a 27% reduction in contrast to the bare PV system and a 16% reduction when compared to the PV/W system. By lowering the temperature, the new PV/SW system increased average electricity efficiency by 43% over the normal PV system and by 12% over the PV/W system. By circulating an Al_2O_3 nanofluid in two distinct flow patterns, Othman Mohammed Jasim *et al.* [16] carried out an experimental investigation of PV/T collector cooling using energy and exergy analysis. The PV module was used to produce a PV/T-A collector model. In order to facilitate the circulation of Al_2O_3 nanofluid, a copper coil tube was installed at the rear of the module. This circulation was made possible by the polyamide channel structure, which served as a PV/T-B collector and was affixed to the back of the PV module. In comparison to the standard PV, PV/T-A and PV/T-B were cooled 28.94% and 48.54% better, respectively. PV, PV/T-A, and PV/T-B have energy efficiencies of 4.78%, 42%, and 52.52%, respectively, whereas their exergy efficiencies were 5.01%, 7.35%, and 9.42%, respectively. PV/T hybrid solar collectors were researched theoretically as well as experimentally by Abdelkrim Khelifa *et al.* [17]. With the goal of eliminating heat from the photovoltaic module, the system under investigation consisted of a tube and sheet positioned underneath the surface where the solar cells are formed. It was observed that the efficiency of the solar cell is increased when heat exchanger integrated into the collector lowers the cell's temperature. Haitham M.S Bahaidarah *et al.* [18] conducted research on uniform as well as non-uniform PV string cooling strategies using Dhahran, Saudi Arabia's climate data. Jet impingement design was modeled and investigated in order to provide PV panels with homogeneous cooling. A heat exchanger of the rectangular channel type was studied and contrasted with PV string, which was not cooled in order to assess the impact of non-uniformity. When compared to the heat exchanger's performance, it was discovered that the jet cooling method had a greater efficiency, lowest cell temperature, and temperature uniformity. B. Rajasekaran *et al.* [19] tested the performance of the graphene-incorporated phase change material Paraffin wax and the nanoparticle combination using a finned heat sink with a continuous heat input. When the heat input was 15 W, the fin-equipped heat sink with nano PCM outperformed the baseline heat sink by 30%. Adjusting the heat input to 30 W raised this performance to 45%. The findings showed that regardless of the fins' effect, the phase change material's nanoparticles lengthen the heat sink's recovery time. Gabriel Colt [20] implemented a forced water heat exchanger in order to simulate the cooling effect on PV panel. Research findings signified that adding a cooling system to a photovoltaic panel increases its output power by approximately 12.5% during very warm weather. The PV/T system produces approximately 25% more energy overall when the heat from the PV panel that is transferred to the cooling water is taken into account. It was observed that the Panel efficiency augmented by 57% when active water cooling prompted the panel's temperature to drop by roughly 32%. The impact of cooling the photovoltaic cell's back part on the device's efficiency and ability to generate electricity was examined experimentally by S.M. Shalaby *et al.* [21]. He tested one PV module with cooling and one without at the same time using two identical modules. Results showed a 14.1% uplift in the power yield when the planned cooling system was installed. During testing, it was noted that the electrical efficiency reached 19.8% when the PV module was equipped with a cooling system. When testing was not subjected to cooling it reached only 17.4%. Cheng Siong *et al.* [22] investigated the cooling technique by lowering the PV panel's operating temperature with a cold plate fastened to it. Trial results revealed that, in contrast to a panel unaccompanied by a cooling system, the surface temperature decreased by around 21.2 °C, and the electrical, thermal, and PV panel efficiency improved by about 2%, 8%, and 1.6%, respectively. By including a heat exchanger with the intention of cooling back surface of the PV module, Haitham Muhammad S. Bahaidarah *et al.* [23] found out what happened when they cooled the module experimentally. Moreover, results from experimental climatic measurements in the Saudi Arabian city of Dhahran were found to be highly concordant with the numerical model. By reducing module temperature to around 20% with the implementation of active cooling utilizing water, efficiency of the panel was noted to enhance by 9%. Experimental analysis of a 100-W PV panel with an automatic water-cooling system was conducted by Hussain Attia *et al.* [24] in the United Arab Emirates' climate. The water cooling system was run intermittently in the chosen method, with a 2-minute cooling cycle occurring every 30 minutes during the day. With respect to the total harvested energy, testing results showed that PV system performance improved by around 1.6% when compared to the uncooled system. Ali Sohani *et al.* [25] examined the effectiveness of a water-flow cooling system to boost the output of an 80 W monocrystalline PV panel from both energy and an exergy standpoint. The results demonstrate that the when water-flow cooling is employed, improvements in regular average energy efficiency range from 7.3% to 12.4% depending on the season. Additionally, the increase in energy efficiency that was attained falls between 13.0% and 19.6%. Fabio Schiroa *et al.* [26] investigated if it would be feasible to retrofit current solar units with cooling systems without altering the construction of the modules themselves. The technique chosen for cooling module from the front side necessitates the use of water. As the weather causes uncooled solar panel to become hot, the cooling system's ability to increase energy gain is maximized.

Cooling strategies fall into two categories: Active cooling and passive cooling and are utilized to diminish the operating temperatures of solar panel [27]. These cooling solutions are mostly used for removing bulk of the heat from the solar panel, owing to which its overall performance improves [28]. While passive cooling typically involves dissipating the heat into the atmosphere, active cooling should take waste heat usage into account since it is pivotal to the financial feasibility of the cooling technique being scrutinized.

Active cooling is the process of cooling a PV panel by continuously using power. Natural convection or conduction is used in the passive cooling approach to facilitate heat extraction. Since active cooling techniques rely on air or water cooling, the system that uses power is a pump or fan that helps to keep the fluids moving. Even while active cooling methods usually lead to more usable thermal energy and better power output, power consumption is seen as a big drawback [29]. Thus, when cooling PV panels, water and air are often the coolants employed. In contrast to water cooling, air cooling requires less energy. Water, on the other hand, has a greater capacity for cooling than air, making it a useful method for cooling PV panels. This is because water removes most of the heat from the panel's surface, lowering their temperature and increasing their efficiency [30].

The comprehensive review of the literature revealed a research gap: High temperatures negatively impact PV panel efficiency; therefore, cooling is necessary to mitigate the negative impacts of high temperatures. Both the front and rear sides of the PV panel can be cooled by any cooling system. However, because of its proven outcomes, cooling from the back is generally acknowledged as a common and efficient technique.

Numerous PV cooling methods, such as jet impingement, finned structures, phase-change materials, and nanofluids, have been investigated in earlier research; however, these approaches are complicated, expensive, and provide limited scalability. Nevertheless, there is a large research gap in creating straightforward, affordable, and readily deployable rear-side water-cooling systems that are especially appropriate for hot and dry areas like Kalaburagi, India, despite the availability of numerous cooling techniques. To fulfill this research gap, we suggest and experimentally evaluate a simple rear-side cold-water cooling technique that may be easily incorporated with conventional PV panels to improve their performance in hot conditions.

2. Materials and methods

2.1. Study location

The planned research was executed on the terrace of Analog and Digital Electronics laboratory in the Computer Science and Engineering department at Khaja Bandanawaz University's Faculty of Engineering and Technology in Kalaburagi city. Figure 1 shows a map of the Indian state of Karnataka with the study area highlighted.

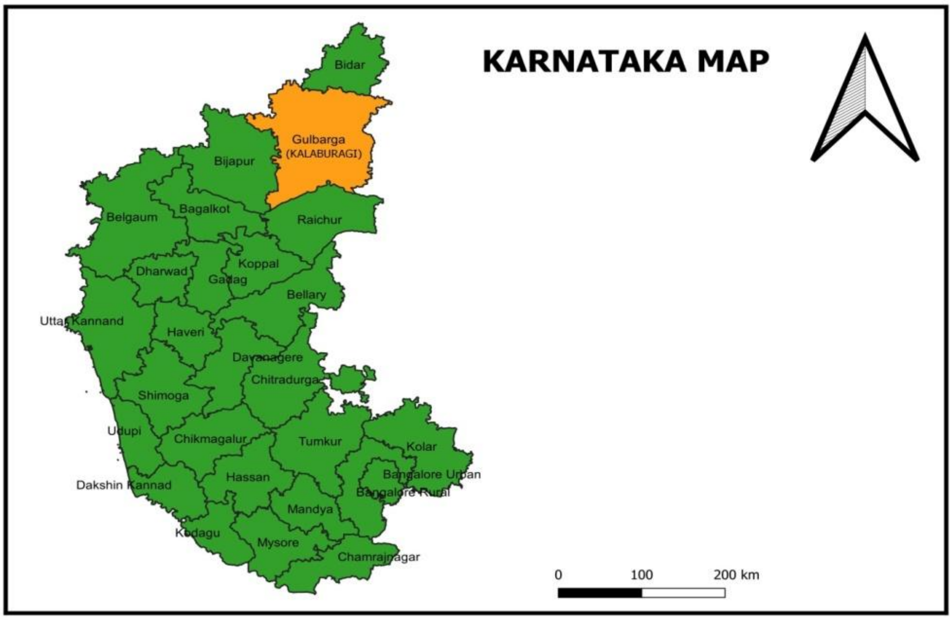


Figure 1. Proposed study area Kalaburagi city.

The study location's geographic details are portrayed in Table 1.

Table 1. Kalaburagi city geographical information.

Geographical parameter	Values
Latitude	17º21′18.64″ N
Longitude	76º51′9.52″ E
Altitude	493 m

2.2. Experimental set up and measurement tools

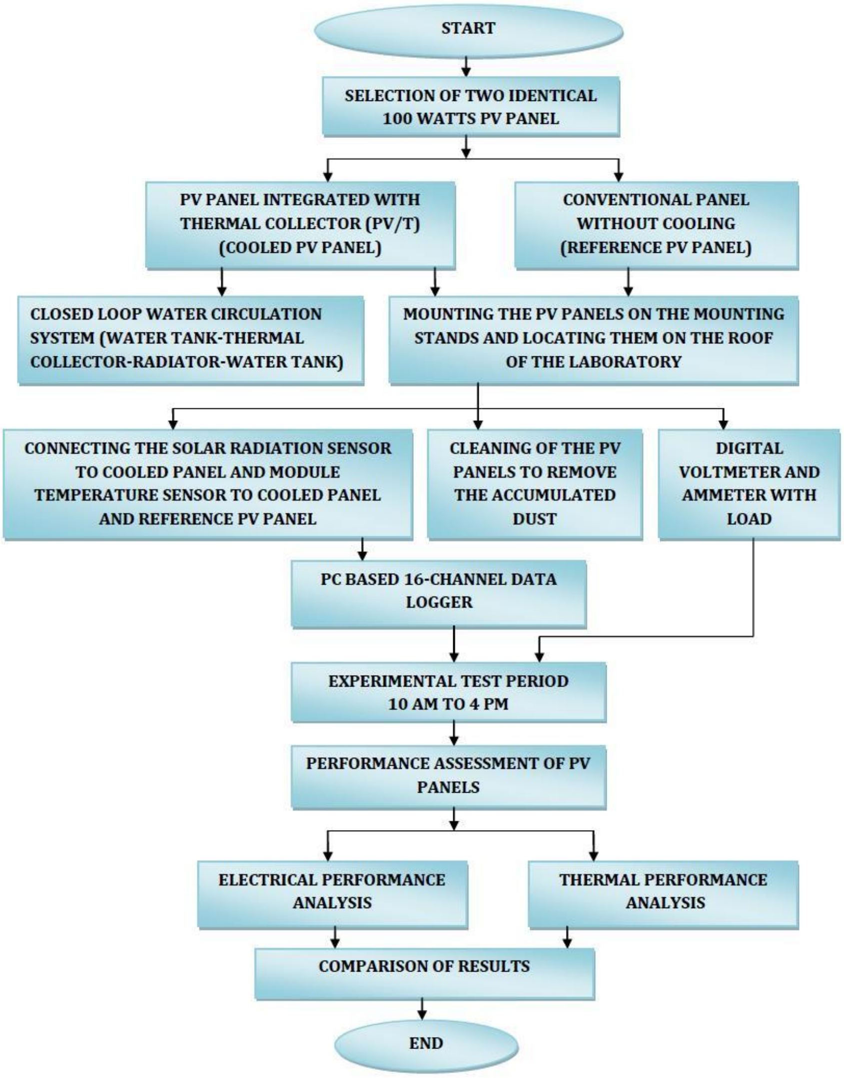


Figure 2. Experimental methodology's flowchart.

The experimental site, where the research was conducted, was first marked in the surrounding area without any shade. Two 100-W polycrystalline PV panels, which were identical in terms of their specifications and manufacturer, were used in the experimental investigation. One of the PV panels was incorporated with thermal technique (PV/T), and the other PV panel served as a reference panel and was not subjected to any thermal technique. After being thoroughly cleaned to remove any dust that may have accumulated, the two PV panels were carefully placed on mounting stands that were strong enough to support the panels. Solar DC cables were used to connect the PV panels electrically through MC4 connectors which are single contact electrical connectors. Figure 2 shows a flowchart that illustrates the experimental methodology's sequential steps.

The estimated measurement error for measuring devices is provided by accuracy. The accuracy and range of measuring instruments used in this study are exhibited in Table 2.

Table 2. Technical specifications of measuring apparatus.

Measuring apparatus	Parameter measured	Measuring range	Accuracy
Solar irradiance sensor PYRA 300C	Solar radiation	0 to 1800 W/m^2	± 3%
Module temperature sensor MSPT 100C	Temperature	0 to 100 °C	± 0.5 °C
Digital DC voltmeter	Voltage	0 to 100 V	± 1%
Digital DC Ammeter	Current	0 to 10 A	± 1%
Data logger	Collection of data from the measuring device and recording it	1 to 16 channels	± 0.25% of reading ± 1 LSD (least significant digit)
Digital thermometer	Temperature (inlet and outlet)	−50 °C to 110 °C	± 1 °C

The precision of the measuring devices in our suggested study is ± 0.25% for the data logger, ± 1% for the digital DC voltmeter and ammeter, ± 1% for the digital thermometer, ± 0.5 °C for the module temperature sensor, and ± 3% for the solar irradiance sensor. The impact of these measurement inaccuracies is typically negligible because they are on the smaller side.

Tabulated in Table 3 are the specs of the PV panels utilized in the experimental investigation.

Table 3. PV panel specifications.

Technical specifications	Rating/Values
Module type	100 W_p Polycrystalline PV module
Module area	0.67 m^2
Module weight	15 kg
Module size	1 m × 0.67 m × 0.03 m
Number of cells	32
Open circuit voltage (V_{OC})	21.9 V
Short circuit current (I_{SC})	6.05 A
Voltage at maximum power point (V_{mp})	18.1 V
Current at maximum power point (Imp)	5.76 A
Fill factor (FF)	78.6%

The experiment lasted six hours from 10 a.m. to 4 p.m. After the system stabilized, twelve readings were taken throughout the course of six continuous hours, separated into half-hour intervals from 10.30 a.m. to 4 p.m. Measurements of solar radiation, ambient temperature, module surface temperature, voltage, and current for the cooled and uncooled panel were recorded every 30 minutes. The solar radiation light intensity level was measured in W/m^2 using solar radiation sensor E-PYRA 300C, which was attached to the mounting stand where the cooled PV panel was mounted. Both PV panels' temperatures were measured in degrees Celsius using a module surface temperature sensor (MSPT 100C) attached to the back surface of the panels. Temperature measurements were also made at the water flow's inlet (PV backside's input via copper tubes) and outflow (the radiator) using a digital thermometer. The experimental setup's data collection was used to examine the temperature characteristics and analyze the electrical and thermal performance of the cooled and uncooled panel. A PC based 16 channel data logger was positioned next to a desktop computer that was set up in the lab. The data logger and desktop computer were connected via an RS485 to USB converter. The data logger dial displayed the measured values of solar radiation as well as temperature, which were also recorded on the desktop computer. The electrical circuit board was equipped with a digital voltmeter for voltage measurement and a digital ammeter for current measurement. Additionally, the electrical circuit board had the DC lamp load installed. A block diagram of the entire experimental setup is displayed in Figure 3.

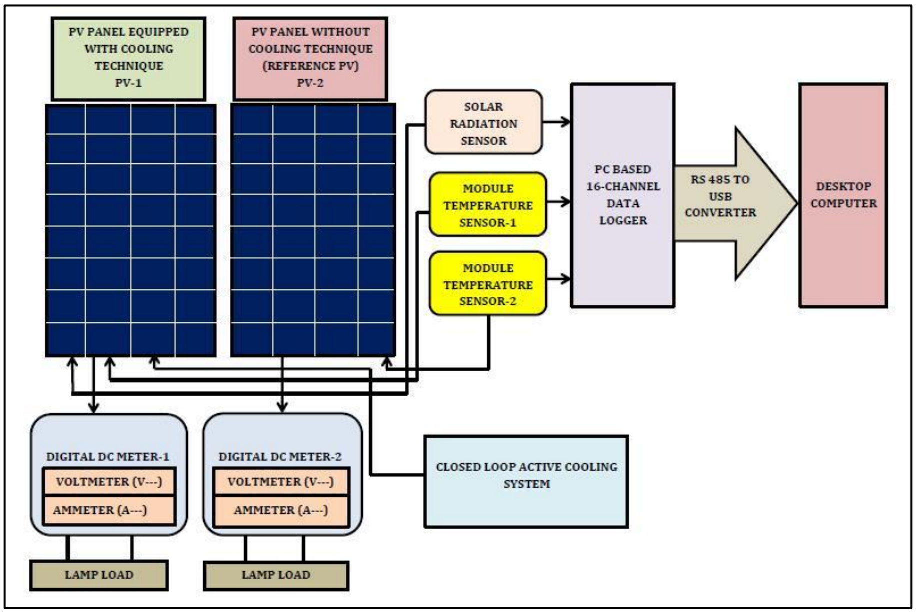
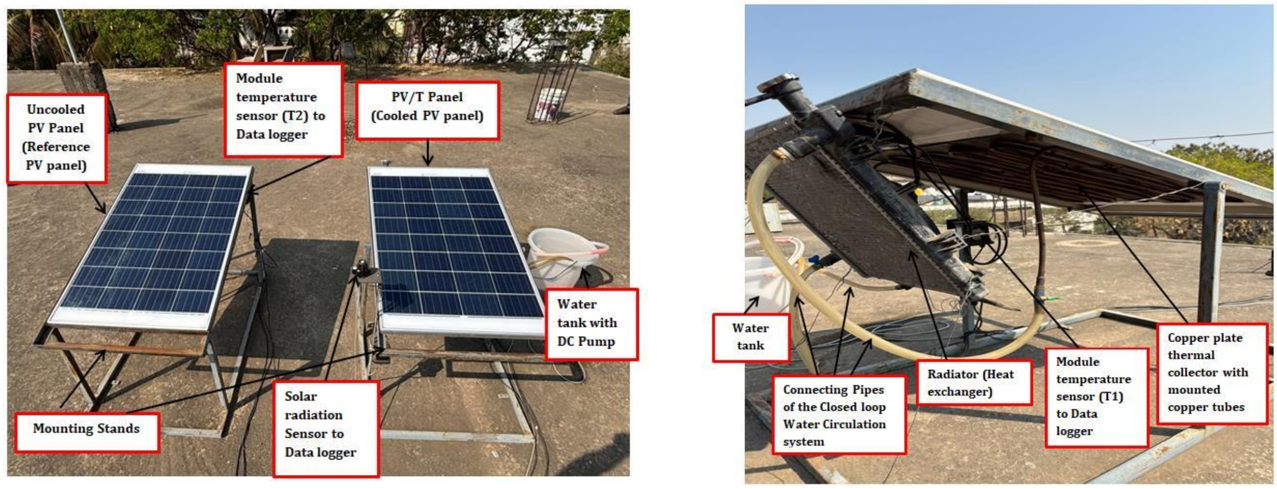


Figure 3. Experimental set up block diagram.

Figure 4 depicts photographic images of the experimental configuration.



(a) (b)

Figure 4. Photographic frontal view of the experimental configuration (a) and photographic image of side view depicting PV/T panel (b).

2.3. The cooling system's experimental design and description

On the basis of literature review, radiator-type heat exchanger and a thermal collector were chosen for this proposed active cooling system. The thermal collector was designed using a copper plate that was 0.76 m in length and 0.58 m in width. By utilizing copper welding rods and the gas metal arc welding procedure, copper tubes with a 0.95 cm diameter were joined to the copper plate of 1 mm thickness. This provided optimal heat transmission speed because the welding rods, tubes, and plate were all made of the same metal, copper. The copper tubes were drawn in the shape of a serpentine shape using a tube bender, and their total length attached to the copper plate was 8.53 m. The role of the copper plate was to help in consistent heat transmission from the panel's front surface to its back surface and then to the copper tubes. Utilizing a metal to glass connecting grease (heat sink paste), which is a good heat conductivity media, the thermal collector assembly was fastened to the panel's rear surface in order to maximize heat transfer from its back surface to the copper plate. When module temperature rose, water running through the thermal collector would remove more sensible heat.

Heat exchanger cooling was utilized in this investigation. Even though the water-cooling system, in particular, has superior cooling power compared with other active cooling strategies, the solar panel's electrical performance may deteriorate after a prolonged submersion in water. For this reason, we made use of a low-cost, specially engineered thermal collector that did not need to be submerged directly in open potable water. By preventing the PV panel from being directly submerged in water, the suggested back-surface thermal collector lowered the possibility of water damage and made the system inexpensive and simple to install into already-existing PV panels. This increased its likelihood of being widely used in rooftop solar systems. Solar PV panel, thermal collector mounted on the panel's back, water supply tank, cold water coolant, mini submersible DC pump, radiator heat exchanger, and water pipes for water flow were arranged in a closed loop system. In this arrangement, the radiator served as the heat exchanger, rejecting the absorbed heat to the ambient environment through convection, while the thermal collector removed heat from the panel surface. The innovative feature of this study was the integration of the benefits of a water cooling system with a thermal collector coupled with a radiator style heat exchanger to provide an efficient PV cooling system that reduced surface temperature and enhanced panel performance.

To cool the panel to minimize its surface temperature, cold water was one of the foremost cooling choices. Since water was a readily available coolant for any cooling system, it was chosen above other coolants for the proposed research because it lowers the PV panel's cooling expenses. While serving as a coolant, water also fulfils two vital functions: Cleaning the PV panel and lowering its temperature, which subsequently increases power output. The cold water, which was used in the cooling process, was pumped through the copper tubes of the thermal collector in a closed cycle. The heat from the panel was extracted by the cold water using a radiator-style heat exchanger. To extract the cooling fluid from the water supply tank, a small 12 Volt DC submersible pump was utilized. The schematic diagram shown in Figure 5 depicts the complete water circulation process in a closed loop system.

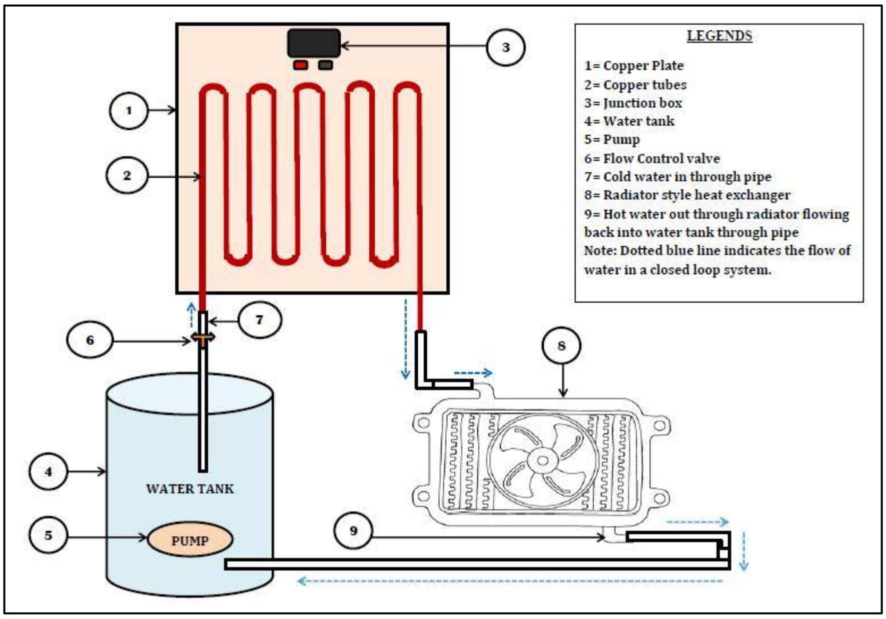


Figure 5. Schematic diagram illustrating the flow of water in a closed loop system.

The surface temperature and the amount of heat withdrawn from the panel was considerably impacted by the flow rate at which water was forced to circulate through the copper pipes. The throttle valve, situated near the intake line of the pump, was used to regulate and sustain the water flow rate.

3. Mathematical modeling

The evaluation of PV panel performance is governed by theoretical equations.

The input power to the PV panel P_{input} can be determined using Eq (1):

$$P_{input} = A_{Panel} \times G \tag{1}$$

where A_{panel} indicates area of the panel in m^2, and G denotes solar radiation in W/m^2.

PV panel's electrical output power P_{output} can be estimated using Eq (2) below [31]

$$P_{output} = V_{OC} \times I_{SC} \times \text{FF} \tag{2}$$

A fill factor is denoted by FF, where Voc and Isc represent open-circuit voltage in volts and short-circuit current in amperes, respectively.

Using Eq (3), PV panel's electrical efficiency ($\eta_{electrical}$) can be determined [32]

$$\eta_{electrical} = \frac{P_{output}}{P_{\text{input}}} \tag{3}$$

$$\eta_{electrical} = \frac{P_{MP}}{A_{Panel}\, X\, G} = \frac{V_{MP} \text{ x } I_{MP}}{A_{Panel} \text{ x G}} = \frac{V_{OC} \times I_{SC} \times \text{FF}}{A_{Panel} \text{ x G}} \tag{4}$$

where P_{MP} refers to the maximum power output of the panel in watts, and V_{MP} and I_{MP} denote the voltage and current at maximum power, respectively.

The heat gain of the water to the incident solar radiation on the PV panel is termed as thermal efficiency ($\eta_{thermal}$), and is computed using Eq (5) [33]

$$\eta_{thermal} = \frac{\text{Q}}{A_{Panel} \text{ x G}} \tag{5}$$

where Q is determined using Eq (6) and represents the system's overall heat gain.

$$\text{Q} = \dot{\text{m}} \times C_P \times (T_{out} - T_{\text{in}}) \tag{6}$$

T_{in} defines water temperature at the inlet in °C, while T_{out} represents water temperature at the outlet in °C, C_P is the specific heat of the fluid (water in our proposed system) with a value of 4184 j/kg, and ṁ indicates mass flow rate of water in kg/s.

$$\eta_{thermal} = \frac{\dot{\text{m}} \text{ x } C_P \text{ x } (T_{out} - T_{in})}{A_{Panel} \text{ x G}} \tag{7}$$

The total efficiency is calculated using Eq (8)

$$\eta_{total} = \eta_{electrical} + \eta_{thermal} \tag{8}$$

Widely employed in fluid dynamics, Reynolds number is a dimensionless quantity that calculates ratio of the inertial to viscous forces and assists in predicting flow patterns of fluid in a variety of situations [34,35]

$$R_e = \frac{\rho \text{ x v x d}}{\mu} \tag{9}$$

In this case, Re stands for Reynolds number, ρ for fluid density, v for fluid velocity, and d and μ represent pipe diameter and fluid dynamic viscosity, respectively.

For laminar, transitional, and turbulent flows, precise Reynolds number values must be acquired in all practical conditions. The aforementioned Eq (9) is used to accomplish this.

4. Results and discussions

Using the experimental data, performance of the PV/T panel was compared under identical conditions with the reference panel to ensure cross-comparison and validation of the results. Actual theoretical equations for evaluating PV performance mentioned in section 3 were used to accomplish that.

4.1. Solar radiation interrelation with time

Solar radiation is the most important meteorological parameter that significantly affects PV panel output. Examining and analyzing solar radiation is essential due to its remarkable impact on PV module performance. Differences in solar radiation, which were noted on the day of the experiment, are depicted in Figure 6.

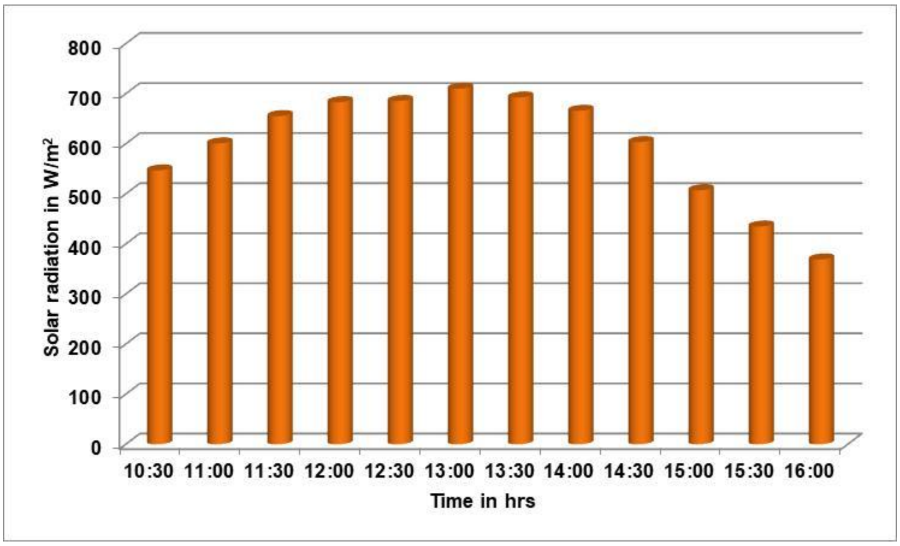


Figure 6. Solar radiation variations recorded during the experiment.

It was noted that midday experiences greater amounts of solar radiation when compared to either the early morning or late afternoon. This provides further evidence that solar radiation levels vary throughout the day. At 1 p.m. and 4 p.m., respectively, the experiment's maximum and minimum recorded solar radiation levels were 710.2 W/m^2 and 369.2 W/m^2, respectively.

4.2. Evaluation of electrical performance

Voltage and current affect how much power the PV module can produce. The solar cells heat up more in response to higher temperatures, which causes a decrease in semiconductor band gap energy, leading to a slight rise in current but a considerable fall in voltage. The fundamental equation that describes a solar cell's open-circuit voltage incorporates temperature as a variable and is given in Eq 10 [36]:

$$V_{OC} = \frac{nkT}{e} ln \frac{I_{ph}}{I_s} \quad (10)$$

where n is the diode quality factor, k is Boltzmann's constant, T is absolute temperature, e is the elementary charge, I_{ph} is the photocurrent or the short circuit current, and I_s is the saturation current.

While the operating temperature of the panel drops, its voltage rises, and it climbs a little when solar radiation rises. It is worth mentioning that fluctuations in solar radiation and the panel's operational temperature also affect current. The PV panel's current rises noticeably as solar radiation levels rise and, to a lesser extent, as the panel's operational temperature rises.

At 1 p.m., the cooled PV panel's output power reached its maximum of 93.97 W. At this moment, solar irradiation was 710.2 W/m^2. However, at 10.30 a. m., when solar radiation was 546.9 W/m^2, its lowest output power noted was 84.83 W. The uncooled PV panel's maximum and minimum output powers were 86.01 W and 82.33 W, respectively. The uncooled panel's highest output power was noted at 1.30 p.m. when the solar irradiance was 692.7 W/m^2, while its lowest output power was recorded at 10.30 a.m. when the solar irradiance was 546.9 W/m^2. Typically, from 11.30 a.m. to 3 p.m. in the late afternoon, there was a noticeable variation in the calculated power production for cooled and uncooled PV panels. The output power fluctuation during the day further highlights the interaction of solar irradiance, temperature, and panel efficiency; the performance difference between cooled and uncooled panels increased between 11.30 a.m. and 3 p.m., when irradiance and ambient temperature were at their maximum.

The PV panels can generate 100 W because their rated power is 100 W. On average, the cooled PV panel generated 90 W of power, whereas the uncooled one generated 84 W. The suggested cooling solution, therefore, achieved a 6 W net gain. Consequently, an improvement of about 8% was achieved. In real-world settings, this translates into significant yearly energy benefits, particularly in areas with high levels of solar radiation and ambient temperatures, where PV modules usually experience significant efficiency declines. The output power variations of both panels are portrayed in Figure 7.

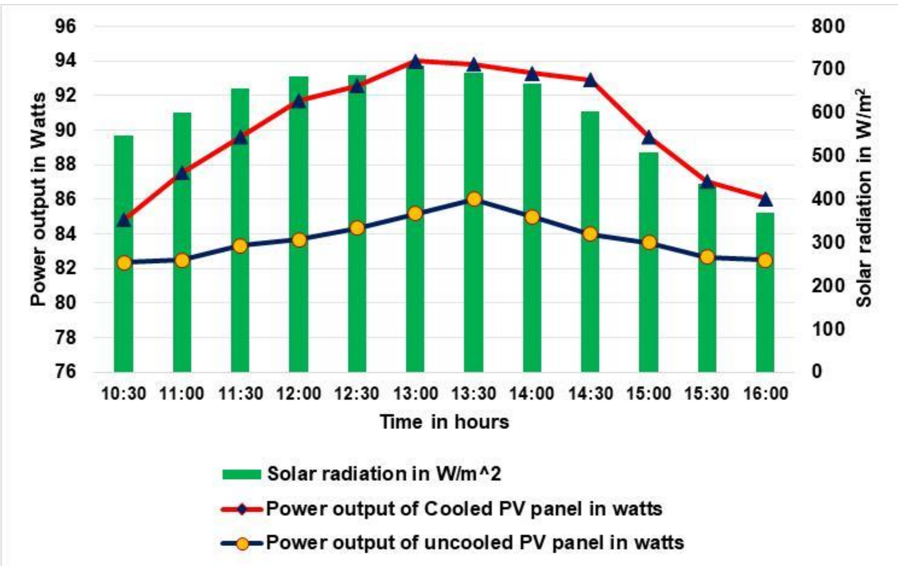


Figure 7. Power output changing with time and solar radiation.

Apart from solar radiation, PV panel efficiency is contingent on its surface temperature. Electrical efficiency of both the PV/T and uncooled panels, measured every 30 minutes between 10.30 a.m. and 4 p.m., is portrayed in Figure 8.

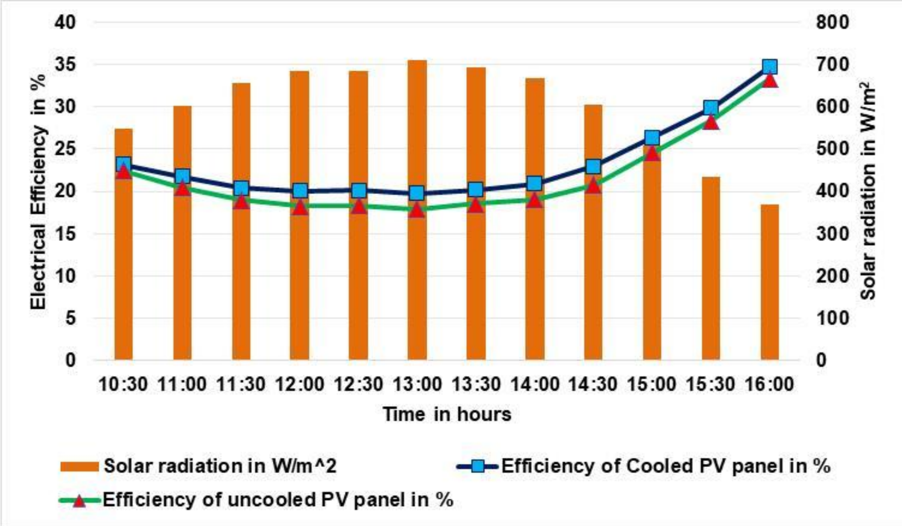


Figure 8. Electrical efficiency changing with time and solar radiation.

The graph shows that midday had the greatest decrease in electricity efficiency, after a morning peak. Extreme heat and intense sunshine were to blame for the low yield of electrical efficiency. Cooled and uncooled PV panels had an average electrical efficiency of 23.35% and 21.75%, respectively.

4.3. Cooling influence on the temperature of the PV panel

The PV panel's temperature rose in tandem with the amount of solar radiation, which impacted its efficiency. Temperature variations of cooled and uncooled panels with the outside temperature recorded during the trial are depicted in Figure 9.

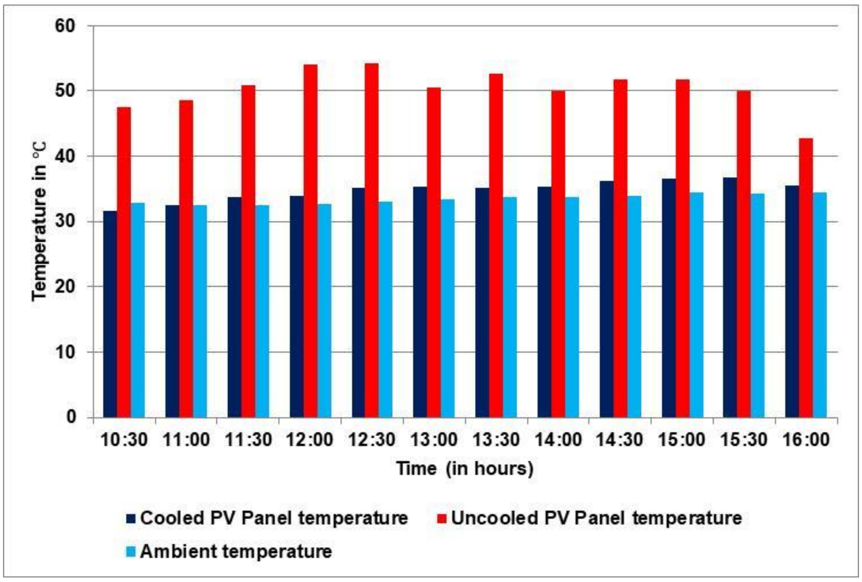


Figure 9. Noted temperature of both panels alongside measured surrounding temperatures.

Figure 9 shows that both panels differ noticeably with regard to module surface temperature. Due to cooling impact of the backside cooling, the operating panel temperature of the cooled panel declined, as anticipated. It was feasible to diminish the temperature to 32 °C with this cooling, which is a significant drop. Alternatively, the uncooled panel temperature varied between 43 °C and 53 °C, with a mean temperature of about 50 °C. Over the course of the investigation, the surrounding temperature fluctuated between 32.5 °C and 34.5 °C. The cooling system was successful in declining the operating temperature by 16 °C, on average. This decline was noteworthy since crystalline silicon PV panel's electrical efficiency usually dropped by 0.4 to 0.5% for every degree Celsius over the standard test environment. Theoretically, the ~16–18 °C drop in our cooled system translated into a 6–8% efficiency gain based on this temperature coefficient, which was rather close to the ~8% improvement that was observed empirically.

4.4. Evaluation of thermal performance

The twofold advantage of the cooling strategy is further supported by the thermal efficiency analysis. Water passing through the copper tube thermal collector's input can absorb heat generated by the PV panel, and thereby results in minimizing the panel's temperature. Apart from solar irradiance, the thermal efficiency of the PV panel is also impacted by its temperature to a greater extent. With an enhancement in the volumetric flow rate, it was ascertained that temperature differential decreased. Using 1.2 and 2.4/min, the experimental temperature differential values were 2.3 °C at the highest and 1.5 °C at the lowest. The thermal efficiency of the PV/T panel was at its peak at 4 p.m. with 64.21% when the volumetric flow rate was set at 1.2 L/min, while the minimum thermal efficiency was recorded at 53.06% at 1.30 p.m. when the volumetric flow rate was maintained at 2.4 L/min. On average, the PV/T panel was 59.6% efficient in terms of heat transfer, which is on par with, or superior to, numbers reported in similar PV/T water-cooled systems (Abdelkrim Khelifa *et al.* [17] Cheng Siong *et al.* [22]).

With this hybrid energy harvesting technique, PV systems can be used as a thermal energy source for space heating and water heating in addition to producing electricity. These two advantages enhance the overall sustainability of the system.

4.4.1. Flow rate's effect on the cooled system functionality

A significant component that affects PV panel temperature is the cooling medium's flow rate. It is noteworthy that the temperature differential was influenced by the fluid flow velocity and the sun radiation, owing to which the PV panel's temperature and, eventually, its performance are directly affected. Water at four distinct flow rates ranging from 1.2 to 2.4 L/min was employed in the proposed experiment since the cooling fluid's flow rate is crucial in improving the energy yield of the panel.

PV panel temperature has considerable impact on its efficiency, as indicated in the literature. By bringing down its temperature, the PV panel efficiency can be elevated. Therefore, it was intended to maintain higher volume flow rates since they tend to provide more cooling, particularly during the high solar radiation hours of 12 to 2.30 p.m. In the early and late afternoon, low volume flow rates of 1.2 and 1.6 L/min were maintained since low levels of solar radiation are witnessed during this time. The findings demonstrated that panel was cooled reasonably well by volume flow rates of 2 and 2.4 L/min, as opposed to 1.2 and 1.6 L/min. This suggests that the temperature increase sharply decreased as the volume flow rate increased.

The power improvement percentage is computed using Eq (11)

$$\%P_{improvement} = \frac{P_{cooled\ PV\ Panel} - P_{uncooled\ PV\ Panel}}{P_{cooled\ PV\ Panel}} x100 \tag{11}$$

where the output power of cooled and uncooled PV panels are denoted by $P_{cooled\ PV\ panel}$ and $P_{uncooled\ PV\ panel}$, respectively.

Equation (12) is used to calculate the percentage decrease in temperature:

$$\%T_{decrease} = \frac{T_{cooled\ PV\ Panel} - T_{uncooled\ PV\ Panel}}{T_{cooled\ PV\ Panel}} x\ 100 \tag{12}$$

where $T_{cooled\ PV\ panel}$ and $T_{uncooled\ PV\ panel}$ represent the temperature of the cooled and uncooled panel, respectively.

The power improvement and % decrease in temperature obtained at four distinct volume flow rates of 1.2, 1.6, 2.0, and 2.4 L/min every half hour interval from 10.30 a.m. to 4 p.m. is illustrated in Figure 10.

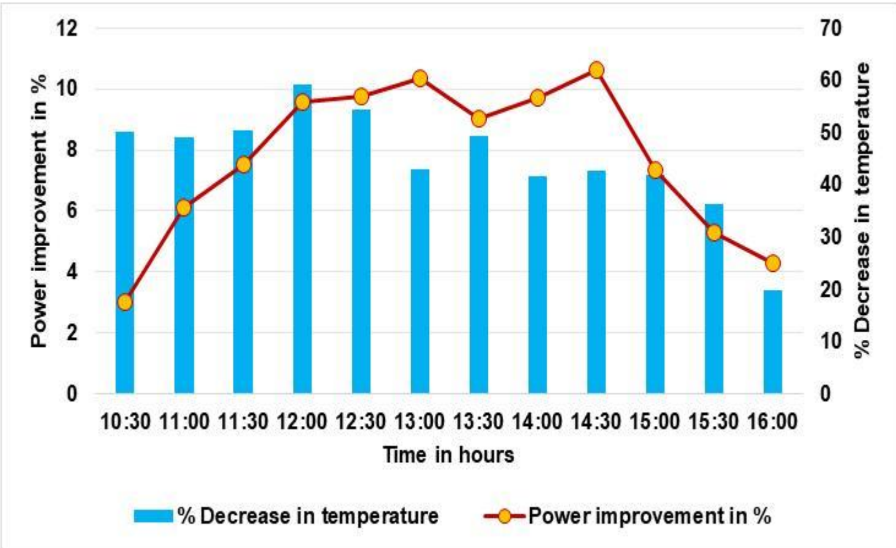


Figure 10. Power improvement and percentage temperature drop at different time of the experimental study period.

The power improvement in the morning was minimal because the panel was running close to its efficient range. Cooling at noon resulted in a greater percentage temperature drop and a greater power improvement. However, in the late afternoon, when the panel temperature and irradiance dropped, cooling had less effect on the power improvement.

4.4.2. Computation of Reynolds number and its impact on flow characteristics

At low Reynolds numbers, laminar flow often dominated the flow through the pipe, although turbulent flow was more prevalent at high Reynolds numbers. Most significantly, if the Reynolds number was below 2300, a laminar flow took place. However, a Reynolds number between 2300 and 4000 was considered to indicate a transitional flow. Alternatively, if it exceeded 4000, turbulent flow was indicated. We used four distinct volume flow rates of 1.2, 1.6, 2.0, and 2.4 L/min in order to push cold water via the thermal collector's copper tubes. Therefore, water flowed at varying velocities. Through the comparison of velocity differences, we can ascertain the Reynolds number and the flow category.

With respect to the volume flow rate values that were implemented in the system, the Reynolds number values that were calculated ranged from 3557 to 7166. As a result, the system was transitioning from the transitional to the turbulent phase. Figure 11 displays the Reynolds number obtained at four distinct volume flow rates during the experimental period.

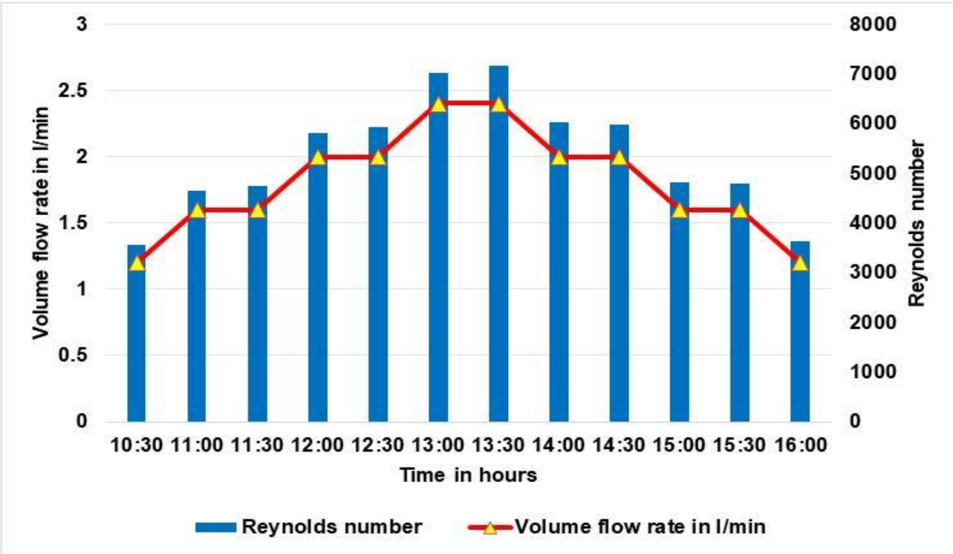


Figure 11. Reynolds number indicating the system moving from transitional to the turbulent phase.

Through testing at various flow rates and Reynolds numbers, the study shows how system performance may be adjusted for turbulent flow to improve efficiency and heat transmission.

Together with the findings of the suggested study, Table 4 summarizes the findings of the experimental studies discussed in section 1 of the literature review.

The credibility of our experimental results is validated by the gains in efficiency, which is in line with other studies reported in Table 4.

Notably, our results were achieved using a straightforward radiator-style heat exchanger, demonstrating that significant improvements can be made without the need for expensive or complicated designs. The system's integration of the cooling mechanism may help reduce long-term material stress brought on by thermal cycling in addition to improving electrical performance. Additionally, the results are very applicable to increasing energy yield, lowering efficiency losses in hot regions and advancing hybrid PV/T systems as a sustainable way to meet the needs for thermal and electrical energy.

Table 4. Comparing the findings with those of other studies.

Authors	Study location	Cooling technique used	Heat exchanger employed	Cooling fluid used with flow rate	Electrical efficiency	Thermal efficiency
Ilaf N. Rasool *et al.*[10]	Erbil city, Iraq	Active cooling (backside water chamber)	Backside water chamber made of acrylic glass 8 mm thick.	Cold Water 3.5 L/min	19.72% (attained)	79.2%
Talib K. Murtadha *et al.*[11]	Mutah University, Hashemite Kingdom of Jordan	Active cooling (Backside cooling)	Copper tube thermal collector integrated with a special tube heat exchanger	Aluminum-oxide nanofluid 1.6 L/min	20.2% (attained)	-
Uzair Nasir *et al.*[13]	NUST University, Islamabad, Pakistan	Active cooling (Backside water cooling piping model	Elliptical copper pipe heat exchanger	Water 0.052 L/sec	4.46% (incremented) for Monocrystalline PV 3.35% (incremented) for Polycrystalline PV	- -
Abdelkrim Khelifa *et al.*[17]	Applied Research Unit for Renewable Energy de Ghardaïa (Southern of Algeria)	Active cooling (Backside water cooling)	Sheet and tube heat exchanger	Water 0.025 kg/s	14.8% (attained)	55%
Haitham M.S Bahaidarah *et al.*[18]	Dhahran, Saudi Arabia	Active cooling (Backside cooling)	i) Jet impingement cooling with nozzles ii) Rectangular channel heat exchanger made of Aluminum (HX)	Water (flow rate not specified)	i)17.2% (attained) (PV string with water jet impingement cooling) ii) 14.6% (attained) (PV string with rectangular channel cooling)	- -

Continued on next page

Authors	Study location	Cooling technique used	Heat exchanger employed	Cooling fluid used with flow rate	Electrical efficiency	Thermal efficiency
Gabriel Colt [20]	Bucharest, Romania	Active cooling (Backside water cooling)	Forced water heat exchanger (Radiator)	Water (flow rate not specified)	57% (incremented)	-
S.M. Shalaby *et al.* [21]	Egypt	Active cooling (Backside water cooling)	PVC tubes	Cold water 0.15 kg/s	19.8% (attained)	-
Cheng Siong *et al.*[22]	Clean Energy Research Centre Temasek Polytechnic, Singapore	Active cooling (Backside water cooling)	Cold plate with guided channels and radiator heat exchanger.	Water 0.15 kg/s	17.2% (attained)	50%
Hussain Attia *et al.* [24]	American University of Ras Al Khaimah, UAE	Active cooling (front surface intermittent cooling)	Manifold positioned at the top of panel surface	Water 11.1 L/min	1.6% (improvement)	-
Md Moyeed Abrar and Sangamesh G. Sakri [Proposed study]	Kalaburagi city, India	Active cooling (Backside water cooling)	Copper tube thermal collector integrated with a radiator style heat exchanger	Cold water 2.4 L/min	23.35% (attained)	59.6%

5. Conclusions

We investigated active rear-surface water cooling for PV panel utilizing a copper tube thermal collector and radiator-style heat exchanger in the hot climate of Kalaburagi city. Testing was done on two identical 100 W polycrystalline panels: One with cooling and one without. The cooled panel outperformed the uncooled panel in terms of electrical efficiency and operating temperature. The principal findings of the conducted research are enumerated below:

1. Reference panel temperatures varied from 43 °C to 53 °C. The average PV/T panel temperature was 35 °C. On average, the cooling system lowered the operating temperature by 16 °C.
2. The cooled panel's output power increased due to a decline in operating temperatures. On average, the cooled panel generated 90 W, and the uncooled panel generated 84 W. Thus, active back surface cooling yielded a 6 W net gain.
3. The PV/T panel's average electrical efficiency was 23.35%, which was a 1.6% improvement from the reference panel's 21.75%. With an average thermal efficiency of 59.6%, it had a total efficiency of 82.95%.
4. The PV/T system is energy-efficient in electrical and thermal ways, because the PV/T system generates thermal energy and electrical energy. In every case, the PV panel generates more thermal energy than electrical energy. The fact that our proposed PV/T system has a greater thermal efficiency (59.6% vs. 23.35%) lends credence to this assertion.
5. The PV/T system was operating at flow rates between 1.2 and 2.4 L/min to attain optimal cooling and efficiency, resulting in Reynolds numbers between 3557 and 7166, indicating that the system was changing from a transitional to a turbulent state.

5.1. Scope for future work

The PV panel fastened with a copper tube thermal collector and a radiator-style heat exchanger can be evaluated for cooling and heat transfer using CFD simulation. Although copper is utilized in this study, future research may entail aluminum collectors. In order to improve the performance of PV panels, future research, including various heat exchangers, coolants, and nanofluids (CuO, TiO_2, ZnO, and Al_2O_3), is advised.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare no conflicts of interest.

Author contributions

Md. Moyeed Abrar contributed to the conceptualization, methodology, resources and fund acquisition of the study. Md. Moyeed Abrar conducted the investigation and formal analysis of the project of the study. Sangamesh G. Sakri contributed to the conceptualization and methodology of the study. Sangamesh G. Sakri provided the visualization and supervision of the study. Md. Moyeed Abrar and Sangamesh G. Sakri prepared the original draft and carried out review and editing.

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