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Heat Transfer Augmentation in Photovoltaic Panels Using Nanofluid Cooling and Phase Change Material

P Maheshkumar[1*], Jagadeesha Seethappa[2], Suresh Kumar Ramasamy[3], Jayanthi Narayanaswamy[4], Mayakannan Selvaraju[5] and Karthikeyan Palaniyappan[6]

[1]Department of Mechanical Engineering, Nandha College of Technology, Erode, Tamil Nadu , India
[2]Department of Mathematics, Nitte Meenakshi Institute of Technology, Bengaluru, Karnataka, India
[3]Department of Mechanical Engineering, R.M.K. Engineering College, Chennai, Tamil Nadu, India
[4]Department of Physics, R.M.K. College of Engineering and Technology, Chennai, Tamil Nadu, India
[5]Department of Mechanical Engineering, Vidyaa Vikas College of Engineering and Technology, Namakkal, Tamil Nadu, India
[6]Department of Electrical and Electronics Engineering, Erode Sengunthar Engineering College, Erode, Tamil Nadu, India

[*]Correspondence to:
P Maheskumar
Department of Mechanical Engineering,
Nandha College of Technology,
Erode, Tamil Nadu, India.
E-mail: kannanselva1986@gmail.com

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Abstract

The efficiency of photovoltaic (PV) panels degrades when the ambient temperature rises solar radiation absorption. The objective of this experimental research project is to design, construct, and study parametrically a home-based hybrid PV + thermal (PVT) system for active and practical applications of solar panels. As an active cooling mechanism, the PVT system uses water and water-based nanofluids. In addition to investigating the impact of active cooling alone, this article also examines the effect of incorporating phase change material (PCM) and discusses its findings in length. Stable water-based zinc oxide (ZnO) and iron oxide (Fe_2O_3) nanofluids are created in-house using a two-step process with 0.1 and 0.2 vol.% nanoparticle concentrations. The effect of the nanofluids on heat transmission from the PV panel is investigated by measuring and analyzing their thermal conductivity experimentally. The heat transferring rate of nanofluids increases as the number of nanoparticles per unit volume of water increases. At 0.2 vol.%, ZnO-water nanofluid shows the greatest improvement, approximately 30%. The solar simulator is used in an indoor experimental setting to replicate the PVT system under varying levels of solar irradiation (500 - 1100 W/m^2). Combining active and passive cooling at 1100 W/m^2 results in a maximum temperature decrease of around 25% and a gain in electrical efficiency of about 10.3%. When comparing ZnO-water nanofluids with water cooling at 500 W/m^2, it was discovered that using 0.2 vol.% ZnO-water increased electrical efficiency by 13%. The usage of nanofluids, in comparison to water, significantly increased the system's thermal efficacy; the ZnO-basic water nanofluids at a concentration of 0.2 vol.% obtained the highest improvement, approximately 10%. From an operational perspective, these findings are crucial for the development of the PVT system.

Keywords

Nanofluid, Phase change material, Solar radiation, Photovoltaic, Passive cooling

Introduction

Conventional primary energy sources contribute significantly to meeting global energy demand [1]. However, due to increased demand, carbon dioxide emissions into the environment have increased, which has severe effects for the climate and has led to a rise in world average temperatures [2]. Renewable energy sources, on the other hand, have found use in many fields of basic research and engineering. Renewable energy sources are widely available and include solar, biomass, and wind [3]. These renewable power sources are crucial to a long-term solution to the world's pressing energy problems. Direct and indirect utilization of the sun's energy for a wide range of uses has made it one of the most important and suitable permanent energy sources [4]. With the advent of PV panels, solar energy can now be used to generate electricity, allowing the industry to meet its ever-increasing energy needs [5]. In terms of society's long-term progress, PV systems for electricity generation have been shown to be crucial across a wide range of electric energy applications [6]. The electricity, agricultural, cottage industrial, commercial, and social service sectors are just some of the places PV panels have found usage thus far [7]. Solar PV panels are an excellent example of cutting-edge technology in the field of sustainable energy generation [8]. Therefore, renewable technology is used everywhere there is a need for energy. Only around 10 - 15% of the radiation striking a PV panel is converted into usable power; the remainder is absorbed, leading to a temperature rise [9]. Researchers have shown over the past several years that the temperature of the PV cells inside the panels is a major determinant of the panels' electrical efficiency. There is a clear decline in electrical efficiency as panel temperature rises. Every degree Celsius above freezing reduces electrical efficiency by around 0.45% [10]. According to research, increasing the solar panel's temperature from 0 to 75 °C reduces the quantity of power generated from 240 to 195 watts [11]. Another factor is that for every 1 K increase in temperature, the panel's efficiency drops by around 0.4% to 0.65% due to the use of crystalline silicon. Some adjustments to the current PV panel are required to lessen this temperature rise. These changes would involve implementing a back-side cooling technique for PV panels [12]. When a PV panel is cooled, the surface temperature drops significantly, which increases the panel's electrical efficiency. Getting rid of this wasted energy is a necessary step in improving solar cell efficiency and output [13].

PV modules can be protected from overheating by installing a thermal energy absorption to contempt the exhaustion of heat. The PVT collector is a combined system that produces energy and makes use of waste heat from the process [14]. To keep the PV panel cool, fluid is pumped continuously through a thermal absorber, a process known as "active cooling." However, this approach adds the expense of pumping power and upkeep [15].

There are three distinct varieties of PVT collector, all distinguished by the working fluid they employ in the absorber: air, water, and a hybrid of the two. The design of an air-cooled PV panel is straightforward, and the implementation is inexpensive. The PVT collector used by the authors [16] was cooled by air and ducted onto a panel for use. The thermal efficacy of the system was found to rise from 15% at an airflow rate of 0.018 kg/s to 30% at an airflow rate of 0.006 kg/s at the same depth of the channel, as reported by the researchers. The building's projected electricity efficiency also ranged from 12 to 12.4%. Using metrics like energy efficiency and exergy, researchers [17] looked at the effectiveness of glazed and unglazed PVT water frameworks. Three distinct hybridized PVT air-based collector configurations have been evaluated with the same methodology to analyze their energy efficiency, exergy, and carbon credit potential [18]. A PVT collector was presented by the authors [19] and implemented into a solar dryer framework. A hybrid PVT collector was discovered to provide the most optimal air temperature for drying agricultural products. PCM is another method used to maintain a solar cell cooling and boost the panel's energy collecting capacity [20]. When heated to a certain temperature, the latent heat held in a PCM allows the material to release a large amount of energy, making the PCM useful in a number of heating applications [21].

Researchers have conducted many experiments to determine the impact of both active and passive cooling on solar PV panels. Only a small number of studies have looked into the possibility of using both active and passive methods to cool solar PV panels. While there have been a lot of studies looking at the usage of nanofluids application to the cooling of solar PV panels, not enough has been done to increase the overall efficiency of PVT. More experimental studies with varying parameters are needed to comprehend and properly forecast the trend of the PVT features. By using PCM and nanofluids to simultaneously cool PV panels, the system's potential application features may be examined. The major goal of this analysis is to assess the efficacy of the PVT system while it is being cooled by PCM and nanofluids simultaneously. The secondary goal is to characterize the employed nanofluids and offer further data for future sustainable uses of the highly efficient PVT technology. This study analyses experimental findings of hybrid PVT performance with various designs and cooling methods. Water and nanofluids are used in the PVT collector's design, and their performance is compared to that of a traditional PV panel. The system is also put through its paces using PCM cooling, which is combined with active cooling throughout the testing process. Each system is carefully examined for its electrical efficiency, panel temperature, and thermal gain under varying levels of solar irradiation, kinds of nanofluids, and concentrations of nanofluids, and the results of these experiments are published.

Methodology

A monocrystalline PV module with 18 bright lights mounted above the PV panel simulates solar energy production with consistent illumination from 0 to 1110 W/m^2. The solar simulator has an adjustable iron frame and uses halogen lighting. A voltage regulator is linked to the simulator so that the value of the simulated solar irradiation may be adjusted as needed. A pyranometer measures the solar intensity across the PV panel. The experimental layout is depicted in figure 1. The PV panel is made up of PV cells coated with ethylene-vinyl acetate and sandwiched between a Tedlar layer and a sheet of clear glass. Table 1 details the module's specifications. To create a hybrid thermal PVT collector, a container made of aluminum is integrated into the rear of the PV panel. Aluminum storage containers are chosen for PCMs. Aluminum was chosen because of its many desirable properties as a lightweight, inexpensive, high-performance heat conductor, simple, and versatile metal.

Small screws secure the PCM container to the rear of the PV panel once it has been manufactured. The top of the

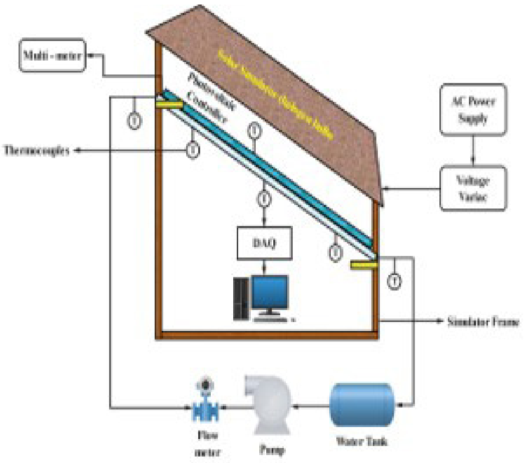

Figure 1: An experimental setup schematic with the PVT collector.

Table 1: Description of the PVT collector.

Criteria	Description
Category of cell	Monocrystalline
Open circuit voltage (V)	22
Number of cells	36
Optimal voltage of power (B)	22.6
Short circuit current (A)	2.6
Thermal absorber area (m^2)	0.35
PV panel maximum capacity (W)	36
Filled factor	0.636
Absorber type	Copper tube
Optimum operating current (A)	1.71
PV panel area (m^2)	0.39

container is insulated from the back of the PV panel using silver thermal compounds (6 W/mK) thermal paste to guarantee efficient heat transfer. In order to maximize the transfer of heat from the solar panel to the fluid, a copper mesh designed for this purpose is attached to the bottom of the container, as shown in figure 2. Because of its clear effectiveness and ease of production, the parallel flow absorber was selected. All of the PV panels receive the same level of cooling since the fluid is always circulating via the riser tubes. Copper tubes are the suggested material for the thermal absorber. The high thermal conductivity of copper made it an ideal candidate for use as the absorber material, allowing for efficient heat transfer from the back of the PV panel to the heat transfer fluid. Using copper as its absorber material, the suggested thermal absorber would cover about a quarter of the back of a PV panel.

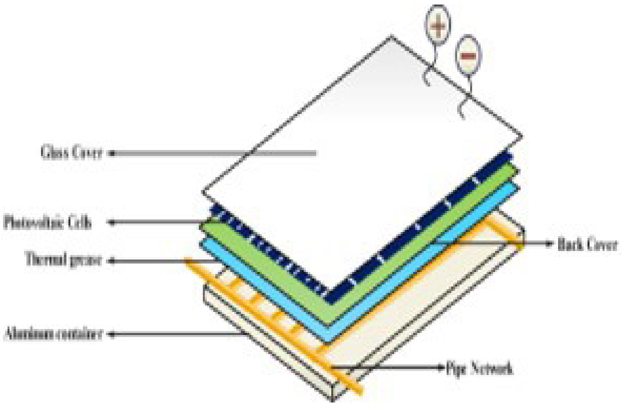

Figure 2: An outline of the experimental testing segment.

The PV rear surface overheat is collected by the PCM and sent to the aluminum container attached to the back of the panel, where it is stored as latent heat. The paraffin wax utilized in the study is an organic PCM chosen for its low cost, stability, nontoxicity, environmentally friendly, and ready availability across a wide temperature spectrum. shows the thermal and physical characteristics of PCM. The KD2 Pro thermal property analyzer is employed to determine the PCM's thermal conduction and specific heat, while a calibrated pycnometer and weighing balance are used to determine the PCM's density. The solar panel's waste heat was converted to latent heat energy by the PCM.

Preparation of nanofluids

Nanofluids refer to a suspension of extremely thermally conductive nanoparticles in a regular base fluid. The most crucial part of the research is determining how long the created nanofluids will remain stable. In this study, nanofluids are synthesized using a two-stage technique. The first stage involves preparing the nanoparticles themselves, which can be done chemically or physically. The second stage of the process utilizes ultrasonication to evenly disperse the nanoparticles throughout the regular base fluid. While there are other options for preparing nanofluids, the two-step procedure is by far the most common approach since it yields a stable product. Using a magnetic stirrer, the selected nanoparticles are mixed with the base fluid for around two to three hours. The probe sonicator was then used to ultrasonically disseminate the mixture for another 4 or 5 h. Both nanoparticles are employed, although at significantly differing quantities of 0.2% and 0.5% by volume. The concentration of nanoparticles is determined by substituting the known densities of the base fluid and the nanoparticles into equation 1 [22, 23].

$$\text{Volume concentration}\left(\text{vol.\%}\right),\varphi=\frac{W_{np}/\rho_{np}}{\left(W_{np}/\rho_{np}+W_{bf}/\rho_{bf}\right)} \quad (1)$$

Using the transient heat source approach, the thermal conduction of the manufactured nanofluid is evaluated using the thermal analyzer. The thermal conductivity was tested many times, and the average value was utilized in the analysis, which reduced the effect of random uncertainty in the results. The following equations are used to analyze the data from the study.

Maximum power output of a PV module is [24].

$$P_{\max}=I_{max}\ \text{x}\ V_{\max} \quad (2)$$

Where 'I_{max}' is maximum allowable operating current and 'V_{max}' is allowable voltage for power.

The PV panel's electrical efficiency may be expressed as [25].

$$\eta_e=\frac{P_{\max}}{I_S A_{panel}} \quad (3)$$

Where 'I_S' is value of solar irradiation and 'A_{panel}' is PV panel surface area.

The thermal efficacy expression for the PVT system is as follows.

$$\eta_S = \frac{Q_u}{I_S A_C} \tag{4}$$

Where 'A_C' is surface area of thermal absorption and 'Q_u' is collection of useful heat.

$$Q_u = c_p\left(T_f - T_i\right) \tag{5}$$

Where 'm' is mass flow rate of the fluid entering the closed-loop system, 'c_p' is specific heat capacity of the fluid, 'T_f' is fluid's temperatures at the system's outlet, 'T_i' fluid's temperatures at the system's inlet, and 'R' is universal gas constant.

Kline and McClintock's approach was used to evaluate the margin of error in the experimental measurements and calculations.

Results and Discussion

The experimental results presented here exhibit the electrical and thermal properties of a PVT solar collector. The behavior of the PV panel is analyzed, and its outputs are thoroughly reviewed, after being subjected to a variety of operating settings and cooling methods. Calculating the zeta potential provides insight into the robustness of the nanofluids. When the zeta potential is larger than 30 mV, the nanoparticles are more easily suspended in the base fluid. Samples of both ZnO-water and Fe_2O_3-water nanofluids exhibit a stable suspension of more than 24 h after synthesis, with zeta values of 45 mV and 40 mV, respectively. Setup for measuring thermal conductivity is checked by comparing it to known values for water at different temperatures [26]. As can be seen in figure 3, increasing the concentration of nanoparticles in a nanofluid results in a dramatic increase in that fluid's thermal conductivity related to that of pure water. ZnO-water nanofluid with a high nanoparticle volume fraction can have a conductivity value up to 30% greater than water.

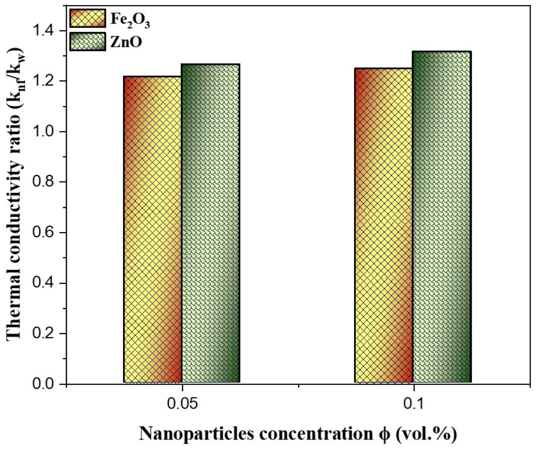

Figure 3: Nanofluid thermal conductivity with respect to nanoparticle concentration at 30 °C.

Without a cooling system, the average backside temperature of a PV panel is indicated in figure 4d at different levels of solar irradiation during a period of around an hour. Temperature fluctuations have been reported to attain a quasi-steady state after around 15 min. Figure 4c displays the time-dependent surface temperature change of a PV panel being cooled with water as the heat transferring fluid, together with the impact of phase change material cooling occurring simultaneously. When PV surface temperature is actively lowered, a noticeable decline may be seen. When exposed to maximum sun irradiation (1100 W/m^2), the surface temperature of the panel drops by around 20 °C. The surface temperature was decreased even more utilizing a combined active and passive cooling strategy. Figure 4a and 4b shows a graph of electrical efficiency vs temperature. As the efficiency charts show, the efficiency drops down exponentially as the surface temperature of the panel rises. Similarly, electrical efficiency decreases when solar irradiation increases because of the dramatic rise in panel surface temperature caused by increased solar irradiation. Compare the electrical efficiency of a passively cooled PV panel (Figure 4b) to that of an actively cooled PV panel (Figure 4a) viewed from behind. PV panel efficiency changes due to active and passive cooling are also discussed.

The electrical efficiency of the PV panel also improves noticeably when active cooling is applied. Combining active and passive cooling methods further enhances energy savings. Findings for cooling solutions for PV panels are in line with those of lower temperatures and higher electrical efficiency.

The impact of temperature on the electrical efficiency of a PV panel under different conditions of solar irradiance and thermal conductivity of the working fluid is shown in figure 5. Five distinct heat transfer fluids' thermal conductivities were

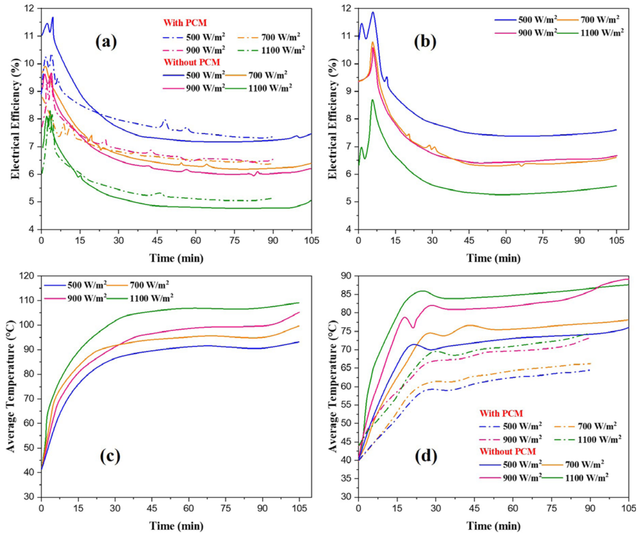

Figure 4: (a) Dynamic cooling (water cooling) and simultaneous cooling (water + PCM) increase the panel's electrical efficiency as shown by the solid and dotted lines, respectively, **(b)** Water-cooled active cooling (solid lines) and PCM and water cooling (dashed lines) are shown for the panel's average temperature, **(c)** The typical temperature of the panel's reverse side when no cooling is applied and **(d)** the effectiveness of electricity without cooling.

determined. Thermal conductivity of fluid has been proven to have a substantial influence in affecting the electrical efficiency of PV, alongside PV surface temperature and solar irradiation values. Efficiency gains are correlated with increasing concentrations of nanofluids. ZnO nanoparticles diluted to a volume fraction of 0.2% in pure water, which had the highest thermal conductivity among the working fluids examined in this study, attained the maximum electrical efficiency. Figure 5 shows that when compared to both no cooling and water cooling, the electrical efficiency gained by using nanofluids is substantial. When sun irradiation trends toward larger values, however, this boost becomes negligible.

Using a range of solar irradiance values, figure 6 depicts the impact of PCM and other fluids on the PV panel's electrical efficacy. For all levels of solar irradiance, employing PCM significantly reduces the surface temperature of PV panels. When related to the other cooling technologies discussed in the article, PCM shows a very slight improvement in electrical efficiency. When the temperature within the cell hits around 50 °C to 60 °C, the PCM begins melting and the excess heat is stored as latent heat. The temperature reduction in the solar collector is around 20 °C when PCM is employed. Figure 6a and 6b show that under low solar irradiation, PCM may attain a peak temperature of up to 50 - 60 °C. Fluid and PCM cooling at the same time have demonstrated good results in lowering the temperature of PV panels. Figure 6c and 6d display a consistent pattern for the more extreme solar irradiant levels.

Several different heat transfer fluids and their respective thermal efficiencies in the PVT solar system are depicted in figure 7. Increasing the nanofluid concentration in the working fluid increases the system's thermal efficiency, as seen in figure 7a. By raising the nanoparticle concentration in the nanofluid, heat conduction between the panel and the working fluid may be increased, hence improving thermal efficiency. Figure 7a demonstrates that an increase of around 10% may be seen with 0.2 vol.% of the ZnO-water nanofluids without PCM related to ordinary water cooling at minimum solar irradiation levels of 500 W/m². Figure 7b shows a similar trend, with PVT cooling with PCM improving thermal efficiency over nanofluid-only PVT cooling. Figure 7b shows that PCM has greater thermal efficiency when compared to Figure 7a.

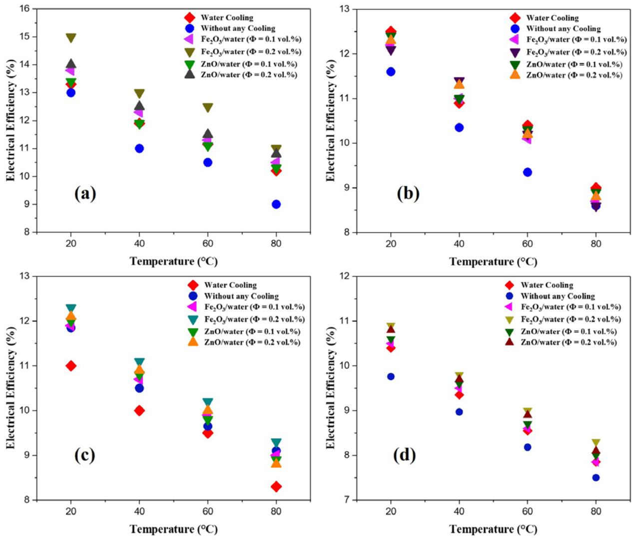

Figure 5: Variation in electrical efficiency of a PV at solar irradiation values of **(a)** 500, **(b)** 700, **(c)** 900, and **(d)** 1100 W/m² with various heat transfer fluids, relative to a stand-alone PV panel without any change at the back-side of the panel.

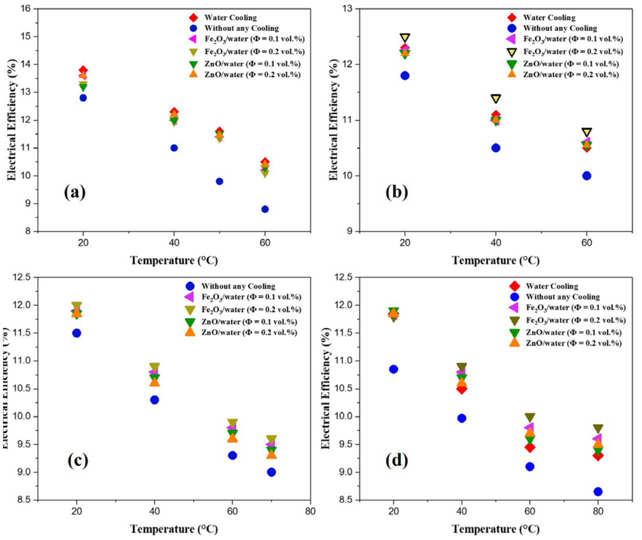

Figure 6: The change in electrical efficacy of the PV cooled concurrently with PCM and other heat transferring fluids at variant solar irradiation levels of **(a)** 500, **(b)** 700, **(c)** 900, and **(d)** 1100 W/m².

Conclusions

The effectiveness of a solar PVT panel setup has been tested using a variety of working fluids in the present experimental study. The electrical and thermal efficiency of the PVT system has been analyzed using a total of four distinct types of nanofluids, with and without PCM. The study concludes with the following.

In this study, nanofluids are created using water as the base fluid, with the addition of ZnO and Fe_2O_3 nanoparticles at concentrations of 0.1 and 0.2 vol.% a surfactant. Utilizing a KD2 Pro thermal property analyzer, the thermal conduction of these nanofluids is measured, demonstrating an enhancement in thermal conductivity as nanoparticle concentrations increase. Without cooling, maximal solar irradiation leads to the PV surface temperature rising to around 95 °C, which stabilizes after 50 min. Introducing water cooling or active cooling effectively reduces the PV surface temperature. Under 500 W/m² solar irradiation, the peak temperature decreases by

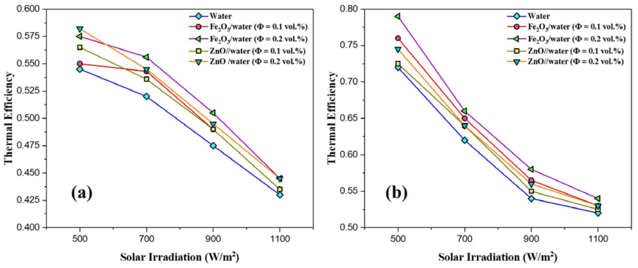

Figure 7: Evaluation of thermal efficacy of solar PVT incorporating variant heat transferring fluids **(a)** without and **(b)** with PCM.

14.2%, while the maximum temperature experiences a 16.3% reduction under 1100 W/m^2 solar irradiation compared to cases with no PV cooling.

- Incorporating passive cooling using PCM alongside water cooling leads to even greater reductions in the surface's peak temperature, as indicated in (iv). Under solar irradiance levels of 500 W/m^2 and 1100 W/m^2, the surface temperature exhibits an additional decrease of 22% and 25%, respectively, compared to water cooling alone. Because the PV panel's surface temperature has such a dramatic effect on its electrical efficiency, that efficiency degrades exponentially as temperature does. At 500 W/m^2 solar irradiance, PV panel efficiency falls below 6%, with a worsened scenario at 1100 W/m^2, both without any cooling measures. Employing water cooling effectively lowers the peak PV panel temperature, consequently enhancing its efficiency. At 500 W/m^2, an improvement of nearly 7% in electrical efficiency is observed, while at 1100 W/m^2, the improvement reaches 10.3%.
- Combining PCM cooling with water cooling yields a remarkable reduction in panel surface temperature, leading to a substantial boost in electrical efficiency. Efficiency experiences a 13% increase at 500 W/m^2 irradiation and notably over 25% at 1100 W/m^2 irradiation. Achieving the lowest temperatures necessitates full coverage of the PV panel's back with the PCM layer, explaining the common use of PCM cooling alongside water cooling. The study delves into the impact of heat transmission fluid thermal conductivity, evaluating five fluids, including water, each possessing varying thermal conductivities. Notably, a ZnO-water nanofluid with 0.2 vol.% exhibits the highest electrical efficiency improvement—roughly 13% over water cooling—due to its superior thermal conductivity. However, this advantage diminishes rapidly with higher irradiation doses.
- Even while electrical efficiency improves little when active and passive cooling techniques are used together, thermal efficiency improves significantly for fluids with better thermal conductivity. Compared to traditional water cooling, the ZnO-water nanofluid without PCM shows an approximate 10% thermal efficiency gain at a lower solar irradiance of 500 W/m^2. The fluid with the highest thermal conductivity proves most effective in terms of thermal gain across varying levels of solar irradiation. Further enhancements in thermal efficiency are achieved when both active and passive cooling are employed together. The ZnO-water nanofluid with 0.2 vol.% concentration exhibits the greatest improvement, around 25%, compared to water cooling with PCM. This research affirms that the inclusion of PCM and nanofluids significantly enhances heat transfer rates, PV panel electricity efficiency, and overall thermal system efficiency. To establish sustainable global-scale solar PVT systems, more investigation into hybridized nanofluids and the utilization of diverse advanced PCM is imperative.

Acknowledgements

None.

Conflict of Interest

None.

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