

Impact of Embedded Pipe Configuration in Phase Change Material on Photovoltaic Cooling

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Abstract

The photovoltaic as a solar power plant is increasingly widespread as renewable energy. However, high photovoltaic surface temperatures can reduce performance in generating electricity. Based on these problems, a photovoltaic cooling system is needed. This research aims to produce effective photovoltaic cooling by planting pipes that carry cold fluid embedded in Phase Change Material. The experimental research used solar simulator, there are three variations of pipe configuration, including: parallel, serpentine, and circular. The photovoltaic used in this research has a specification of 50WP. This study examines the effect of various cooling pipe configurations on thermal performance, output power, and the reduction of photovoltaic temperature. The results show the serpentine pipe configuration exhibits the highest thermal efficiency initially but declines drastically over time, while the circular pipe design demonstrates the best long-term stability and efficiency. Specifically, the circular pipe variation effectively reduces the photovoltaic surface temperature, maintaining the lowest temperature of around 42°C at the 80th minute, compared to higher peak temperatures in the unmodified variation 67°C, serpentine 50°C, and parallel 45°C. Overall, the circular pipe design is identified as the most effective cooling method for maintaining low surface temperatures and ensuring stable performance in photovoltaic panels.

Keywords: Cooling, phase change material, pipe, temperature, photovoltaic.

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INTRODUCTION

Indonesia has great potential in solar energy as it is located on the equator which receives intense sunlight throughout the year. As a tropical country, Indonesia gets high



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solar radiation, fuelling the growing demand for clean and renewable energy technologies to reduce dependence on fossil fuels. Solar energy is recognised as a clean, accessible, sustainable and virtually unlimited source of energy [1]. To utilize this solar energy, Photovoltaic (PV) panel modules are needed. PV cells are able to absorb nearly 80% of sunlight. However, in practice, only a limited fraction of the energy is transformed into electricity, and the efficiency of this conversion largely depends on the technology used in PV production and is conditioned to always be close to the standard test condition temperature point of 25 °C so that the efficiency is maximised [2]. Cooling strategies that reduce thermal loads have also been shown to be effective in keeping PV temperatures close to their standard test conditions [3]. Many researchers around the world are working on PV cooling-related research. This approach aims not only to enhance the photoelectric conversion efficiency but also to extend the operational lifespan of PV modules, which can deteriorate under elevated temperatures [4].

Numerous active and passive cooling methods have been employed to dissipate surplus heat from the PV surface. Based on several methods, the application of Phase Change Materials (PCM) can be used as a cooling medium for PV modules. It is a passive approach that has gained significant attention from researchers lately. Heat absorption originates at the rear side of the PV module. The PCM is an easy and a cost-effective method for regulating the temperature of the photovoltaic system close to the standard test condition temperature and keep the electricity production capacity at the desired level [5]. PCMs absorb a large amount of heat as latent heat at the phase change transition. PV cooling using the principle of latent heat is widely used because of the ability to absorb considerable heat at almost constant temperatures [6]. The PCM absorbs heat transferred from the solar panel, causing its temperature to rise. When the PCM reaches its phase transition temperature, it begins to undergo a phase change, absorbing a significant amount of latent heat in the process, heat absorption still takes place but does not cause a temperature increase again because the energy is used to change the substance form of the PCM [7,8].

Previous studies on PV cooling primarily utilized a single medium, namely water. The results indicated that immersing PV modules in water could enhance their efficiency, achieving a maximum improvement of 4.76% at a water depth of 1 cm. Research by Mehrotra et al [9]. In addition to reducing PV performance, fatal damage due to excessive PV surface temperatures can even damage solar cells as shown in Figure 1. In general, PV cooling systems only consist of one active method or passive method, so this research has the difference of combining the two methods. The PV cooling innovation in this research consists of an active method and a passive method, namely the cooling fluid flowing in the pipe as an active method which is embedded in the PCM as a passive method. There are three variations of pipe configurations, including: parallel, serpentine, and circular. The

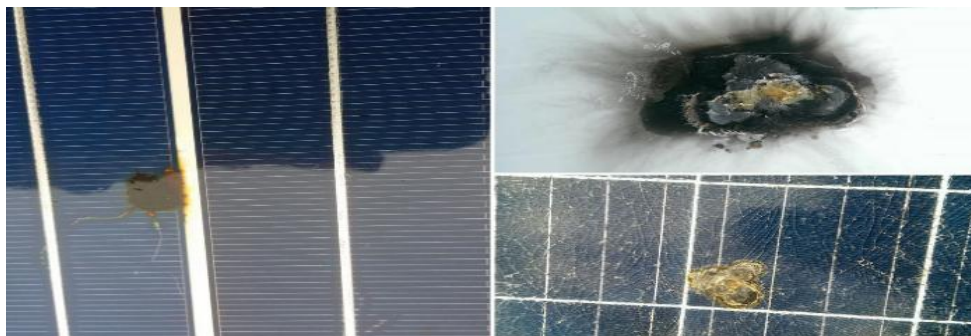


Figure 1. PV surface damage due to overheating [10].

photovoltaics used in this research have a 50WP specification. The method used in this research is laboratory experiments. The results that will be analyzed include PV surface temperature, PV generated power, electrical efficiency, cooling efficiency, and thermal efficiency.

EXPERIMENTAL METHODS

Calculation of PV Refrigeration Equipment Design

At this stage, the design calculation of PV cooling equipment is carried out to determine the right size and configuration to optimize cooling performance and save operational costs. The design of this research can be seen in Figure 2. It consists of design, prototype of PV cooling run in laboratory, and view from pipe that is embedded on PCM. The PCM use Solid Paraffin Wax that has phase change temperature solid – solid 48.16°C and solid – liquid 54.53°C . The cooling water flow inside pipe has mass flow rate 1.7 kg/s , and 32°C of temperature.

Variations Of Pipe Configuration

This stage includes the identification of the research, which includes the selection of tools and materials, system design, data collection and analysis methods, and mathematical models used. Researchers must ensure that all important aspects are considered for a successful study, including effective system planning and determination of appropriate analysis. The experiment variation can be seen in Figure 3. The design and prototype of pipe configurations are parallel, serpentine, and circular that are made from Aluminum can be seen in Figure 3.

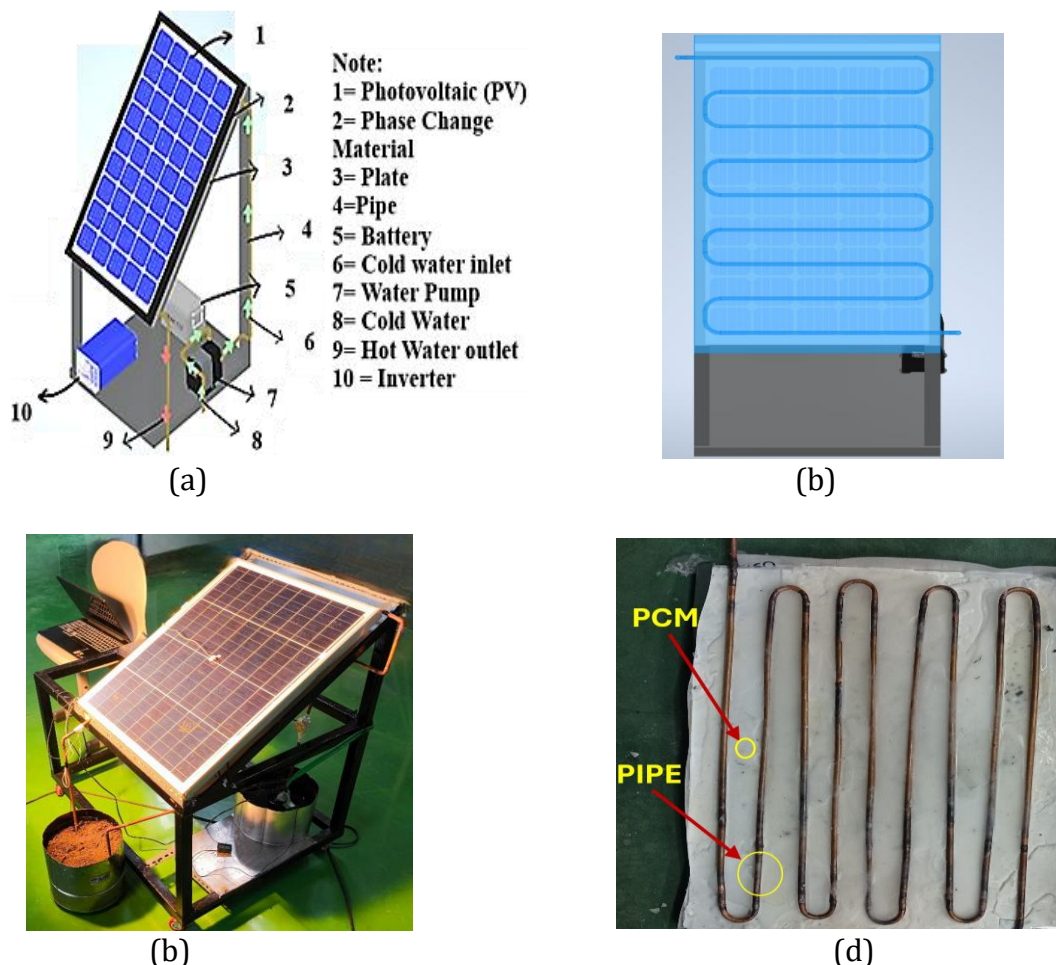


Figure 2. (a) Experimental PV cooling design in isometric view, (b) Experimental PV cooling design in bottom view, (c) prototype, (d) pipe embedded on PCM.

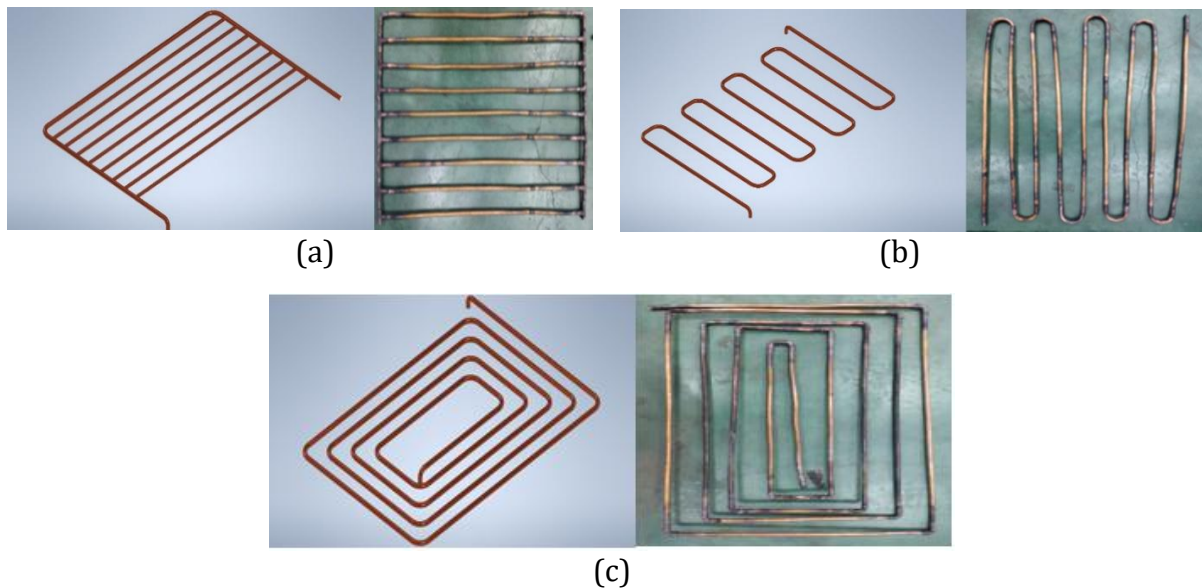


Figure 3. Experiment variation pipe configuration (a) parallel, (b) serpentine, and (c) circular.

PV Cooling Apparatus Manufacture

The manufacture of PV cooling equipment is carried out in accordance with the system design that has been made, varying the pipe arches planted on the PCM to meet the needs of the study to be carried out. This cooling process uses a combination of techniques between PCM and pipe arches that are flowed with cooling Located on the rear side of the photovoltaic module. The following is a picture of the design that has been made.

Calibration of Measuring Instruments

Table 1 shows specifications of Photovoltaic (PV), Table 2 shows specifications of measuring instruments that are used in experiments, and the specification of auto multimeter can be seen in Table 3. The measuring instruments were chosen for their measuring capabilities, appropriate reading range for this experiment, and high accuracy. The measuring instruments have been calibrated to ensure accuracy.

Comparing measurement results between digital and manual measuring instruments is called comparative calibration or comparative calibration. This process is carried out by comparing the measurement results of the tool being tested against other calibrated tools or against a recognized reference standard [11]. Testing of PV cooling equipment is carried out to ensure that it functions properly and the output power is as needed, inclu-

Table 1. PV Specification

PV Specification	
Maximum Power (P_{max})	50 W
Maximum Power Current (I_{mp})	2.75 A
Maximum Power Voltage (V_{mp})	18.24 V
Open Circuit Voltage (V_{oc})	21.8 V
Short Circuit Current (I_{sc})	2.92 A
Standart Temperature Condition (STC)	25 °C
Operating Temperature	-40 - +85 °C
Length x Width	63 x 44 cm

Table 2. Measuring Instrument Specifications MAX6675 K-type

Measuring Instrument Specifications MAX6675 K-type	
Operating voltage	DC5V
Operating current	50mA
Temperature measurement range	-200 to 1300
Accuracy of temperature measurement	1.5
Temperature resolution	0.25
Output specification	SPI digital signal
Storage temperature	-50 -150
Module Weight	4g
Module Size	25mm

Table 3. ZOYI ZT100 Auto Multimeter Digital / Avometer Original continuity

ZOYI ZT100 Auto Multimeter Digital / Avometer Original Continuity	
Battery Type	2 X AAA
Material	ABS
Dimensions	130 X 65 X 32 Mm
Can Display Power Calculations Up To	4000

ding testing surface temperature, output power, and the best pipe bend shape, as well as being a reference for the feasibility of the tool for appropriate applications. Data collection Device testing is carried out based on the operation of PV systems that use a combination of PV cooling with variations in pipe bends embedded in PCMs. In this test, a PV system using PV cooling with variations in pipe bends was embedded in the PCM to optimize PV output power and efficiency. Test data was collected by monitoring Different configurations of pipe bends were studied to enhance the PV system's performance. The measurements taken include the input power from solar radiation, the intensity of solar radiation, and the surface area of the photovoltaic modules. The data collection carries out three repetitions to ensure data stability.

RESULTS AND DISCUSSIONS

The studies employed cooling methods using paraffin PCM and water cooling, which were also proven to enhance both the efficiency and power output of photovoltaic panels. The results of this study indicate that variations in pipe cooling systems such as circular, parallel, and serpentine configurations can lower the temperature of solar panels and increase their power output relative to panels operating without any cooling system. This finding is consistent with research that uses only Paraffin PCM in the back sheet to cool PV from bottom surface conducted by Andri Haris Setiawan et al. [12]. The temperature decreases 2.07% and a power increase of 1.85% demonstrates the effectiveness of using PCM as a passive method to reduce overheating. Meanwhile, the research only used an active method that is water spraying on the top of PV surface, the result showed a reduction in PV panel temperature of up to 10°C, producing the highest power output when the panel temperature reached 45°C by K.A. Moharram [13]. This agrees with research employing air cooling systems for PV panels [14], which also showed notable reductions in surface temperature and efficiency improvements. In comparison, the pipe cooling system in this study offers a relatively simple and passive approach compared to Moharram's active spraying method, while still showing efficiency in maintaining optimal panel temperature and maximizing power output. The performance trend also reflects

findings from experimental evaluations under various climatic conditions, such as those in the eastern Mediterranean, where environmental factors significantly affect PV/T efficiency [15]. Moreover, the circular pipe configuration proved to be the most effective among the tested variations. This is because circular pipes have a larger heat transfer area than other variations. This also results in a greater flow of cooling water within the pipes. The result shows a trend of increased power with higher cooling efficiency like the positive impact observed in previous studies, albeit through different approaches [16][17]. As also supported by nanoparticle-enhanced bio-based PCM applications in open-cell metallic foams to improve thermal conductivity [18] and coupled PCM/fins designs for better temperature regulation [19]. The consistent advantage of the circular pipe variation aligns with prior studies on the optimization of square channel pipe designs in PV/T collectors to enhance heat transfer and maintain stability [20].

Solar Simulator Intensity, Voltage, and Current

This study uses a control variable in the form of solar intensity that is replaced by the solar simulator, to match the actual solar intensity. Figure 4 shows the relationship between solar simulator intensity in W/m^2 and PV average temperature in $^{\circ}\text{C}$ against the time experiment in minute. At the 20th minute, the solar simulator has a power of 336 W/m^2 with a PV panel temperature of 33°C . The solar simulator continued to increase dramatically until it peaked at the 80th minute at 1138 W/m^2 , while the PV temperature also increased to 49°C . Subsequently, the solar simulator decreased to 1084 W/m^2 at the 100th minute and continued to decrease to 356 W/m^2 at the 180th minute. Figure 4 shows an increase in the surface temperature of PV. This occurs because as the day progresses, the sun rises higher in the sky, so that the solar radiation received by the earth's surface and PV panels increases. This causes an increase in the intensity of sunlight and heating of the panel surface, so that the PV temperature also increases.

Figure 5 shows the relationship between solar simulator intensity and open-circuit voltage (V_{oc}) of the solar panel against the time experiment in minute. At minute 20, the solar simulator intensity is 336 W/m^2 with V_{oc} at 17.66 V . As time increased, the solar simulator intensity dramatically increased and peaked at minute 80 at 1138 W/m^2 , while V_{oc} also increased to 20.47 V . After that, the solar simulator intensity gradually decreased to 356 W/m^2 at minute 180, and V_{oc} also decreased to 17.92 V . The graph trendline in Figure 5 is caused by a combination of changes in the intensity of the solar simulator radiation and the effect of temperature on the performance of solar panels.

Figure 6 shows the relationship between the solar simulator intensity and the short circuit current (I_{sc}) in Amperes of the solar panel with respect to the solar simulator intensity from minute 20 to 180. In general, Figure 6 shows that both the solar simulator

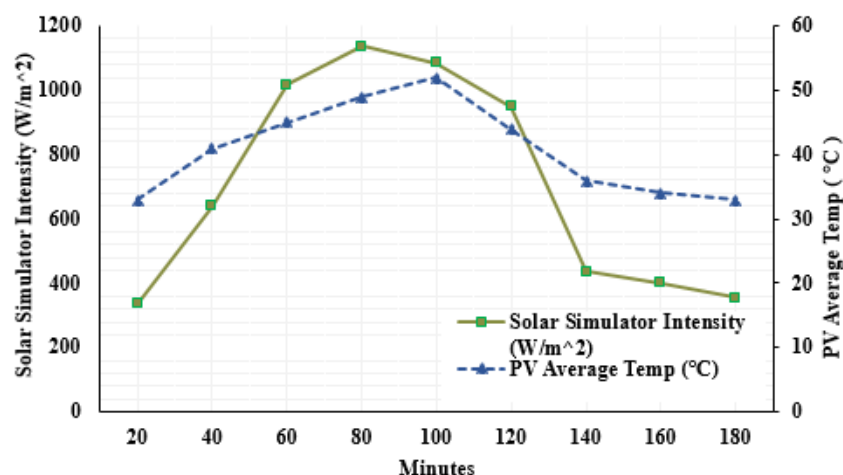


Figure 4. Solar Simulator Intensity and PV average temperature.

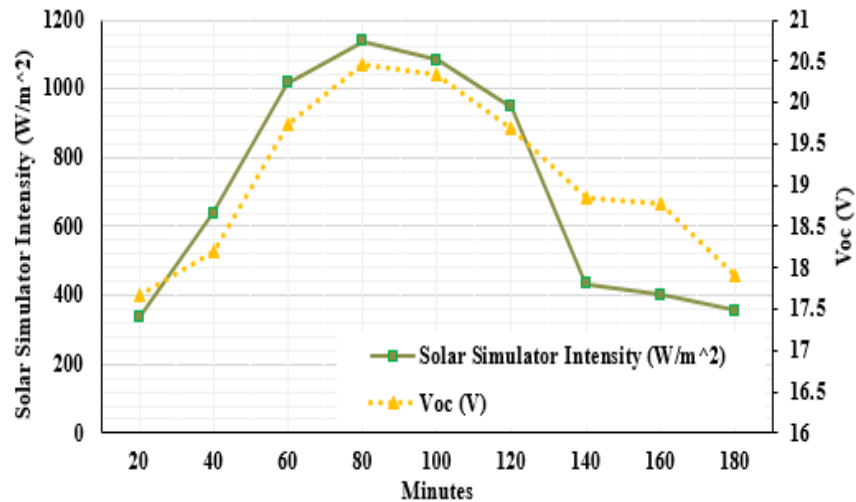


Figure 5. Solar Simulator Intensity and Voc

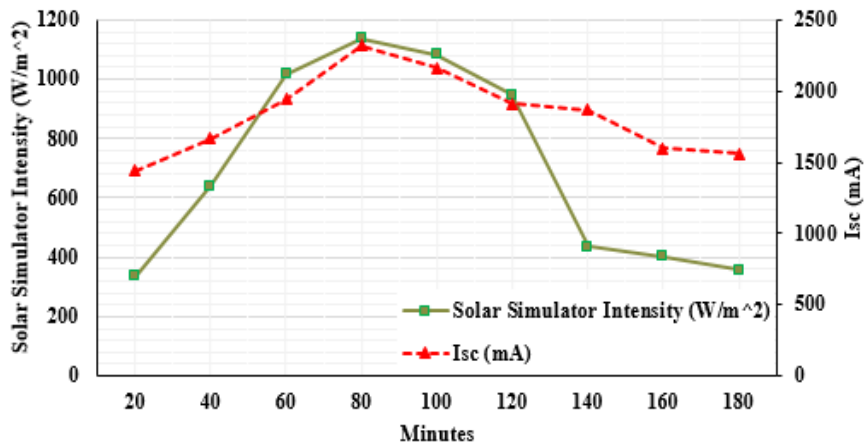


Figure 6. Solar Simulator Intensity and Isc

intensity and the Isc increase from minute 20 until they peak around minute 80 to 100, then gradually decrease until minute 180. At minute 20, the solar simulator intensity was 336 W/m^2 , producing an Isc of 1.44 A. Over time, the intensity increased to 640 W/m^2 at minute 40, with the Isc rising to 1.67 A. The peak intensity occurred at minute 80 with a value of 1138 W/m^2 , and the Isc also reached its highest value at 2.16 A. After that, both parameters began to decline; at minute 140, the solar simulator intensity dropped to 425 W/m^2 and the Isc to 1.6 A, continuing to decrease until minute 180 with an intensity of 356 W/m^2 and an Isc of 1.56. The fluctuations shown in Figure 5 are caused by the fact that the Isc is highly influenced by the intensity of the solar simulator on the surface of the solar panel. The fluctuations in Figure 6 occur because the short-circuit current (Isc) is highly dependent on the amount of sunlight (intensity) hitting the surface of the solar panel. The higher the intensity of the sun, the more photon energy is available to generate electric current in the solar cell, causing Isc to increase.

Power Output Generated

Figure 7 shows the relationship between time, power output in Watts, and solar simulator intensity in W/m^2 , as well as the impact of pipe variation on the power generated. The solar simulator intensity rises sharply from minute 20, peaks around minute 80, and then declines by minute 180. The power output generated by the different pipe configurations: no variation, parallel, circular, and serpentine tends to follow the trend of the simulator intensity, although differences are observed among the configurations.

The circular pipe variation shows the highest power output compared to the other configurations, followed by the parallel pipe and serpentine pipe. The no-variation configuration produces the lowest power. Figure 7 illustrates how the temperature of the solar panel (T_{PV}) and the solar simulator intensity (W/m^2) change over time for various pipe-based cooling configurations applied to the solar panel, namely: no variation, parallel pipe, circular pipe, and serpentine pipe. The intensity of the solar simulator increases sharply starting from minute 20, reaching a peak of around $1100 W/m^2$ at minute 80, and then drops significantly until minute 180. Both the solar panel temperature and the simulator intensity increase over time, peaking around minute 80. This pattern is due to the experimental setup, which simulates natural lighting variation using a solar simulator where the light intensity is deliberately adjusted to the sun's daily cycle. The solar panel temperature follows this light intensity pattern because the higher the light intensity from the solar simulator, the more heat energy is absorbed by the panel, resulting in increased temperature.

Temperature Surface PV

Figure 8 shows that the highest PV temperature is reached in the unmodified variation, which is around $67^\circ C$ at the 80th minute. The serpentine pipe variation produces a maximum temperature of about $50^\circ C$, followed by the parallel pipe variation at around $45^\circ C$, and the circular pipe variation at approximately $42^\circ C$ at the same time. After the 80th minute, the temperature in all variations gradually decreases until the 180th minute. From Figure 8, the pipe variation that best reduces the PV surface temperature is the circular pipe. The ups and downs in the graph are caused by changes in the intensity of solar radiation from the simulator, which directly affects the temperature of the panel, as well as the role of the cooling system in slowing down the rise and accelerating the fall in temperature.

Efficiency: Electrical, Cooling, And Thermal.

Figure 9 shows electrical efficiency versus time for three types of flow: parallel, circular, and serpentine. All three have almost the same pattern. The highest efficiency occurs at the 20th minute about 0.11, then decreases sharply to the lowest point at the 80th minute about 0.03. After that, the efficiency increased again until it was close to the initial value at the 180th minute. The difference between flow types is very small, indicating that the flow shape has no significant effect on electrical efficiency. Figure 10 shows the comparison of cooling efficiency against time in minutes for three types of flow configurations, namely parallel, circular, and serpentine.

In general, the three types of flow show a very similar pattern of cooling efficiency change throughout the observation period from the 20th minute to the 180th minute. Ini-

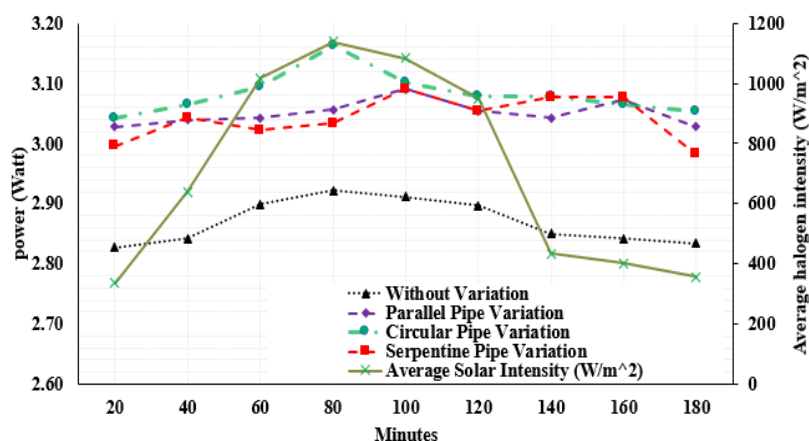


Figure 7. Comparison of power output generated by different solar panels over time with variations in cooling system and solar simulator intensity.

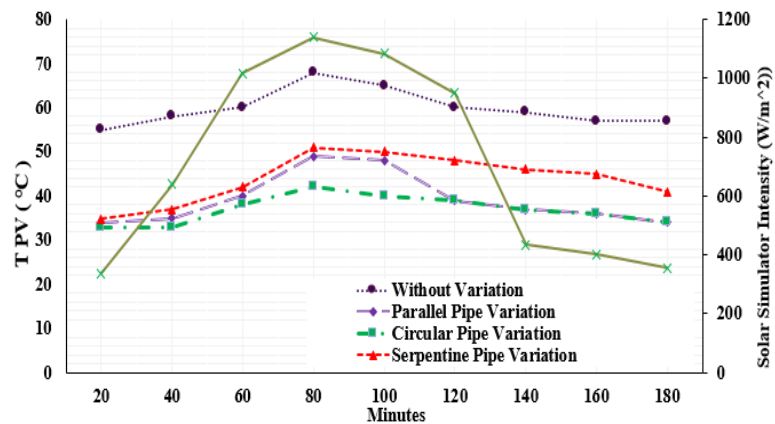


Figure. 8 Relationship between PV time and temperature surface PV with various cooling pipe design variations, and solar simulator intensity.

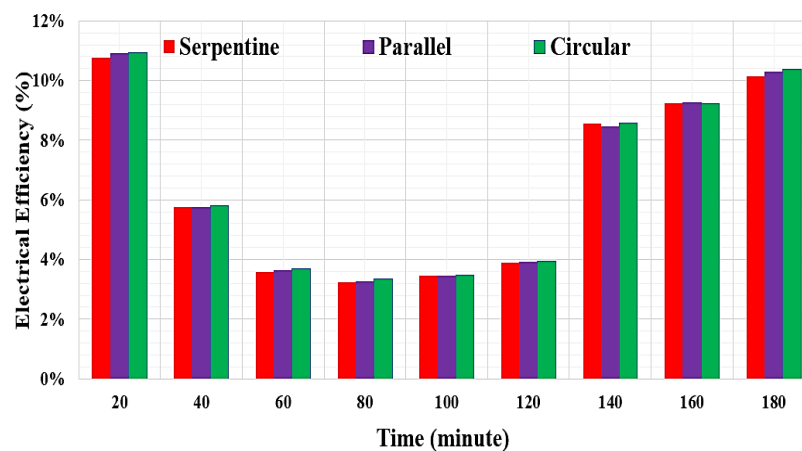


Figure. 9 Comparison of time and electrical efficiency.

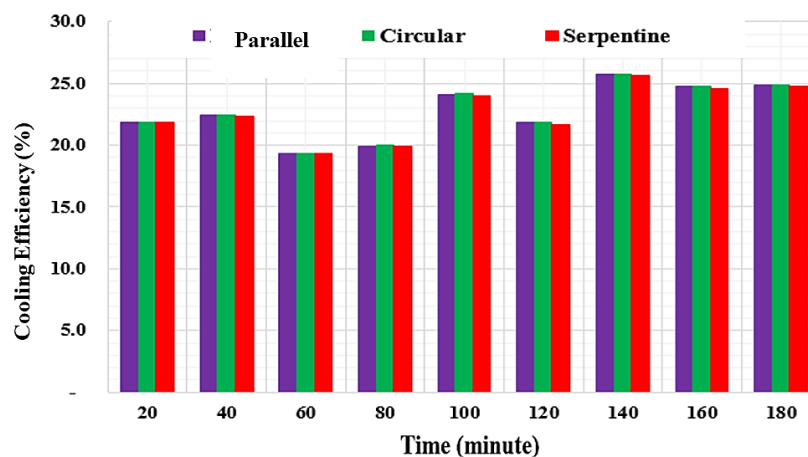


Figure. 10 Comparisons of time and cooling efficiency

tially, the cooling efficiency was in the range of 22-23%, then decreased to about 19% at the 60th minute. After that, efficiency gradually increased again and peaked at about 25-26% in the 140th minute. At the end of the observation time, the efficiency seemed to stabilize near the 25% mark. Based on Figure 9, the difference in flow shape whether parallel, circular, or serpentine does not have a significant effect on cooling efficiency.

Figure 11 shows the change in thermal efficiency of three types of heating channel designs-Parallel, Circular, and Serpentine-over 180 minutes. At the 20th minute, the highest thermal efficiency was shown by the Serpentine design at about 2.8, followed by Circular at about 2.6, and Parallel at about 1.3. After that, all three designs experienced a

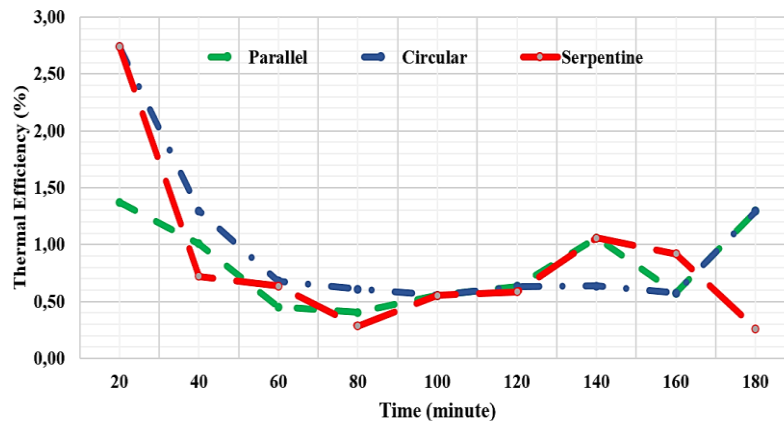


Figure. 11 Comparison of time and thermal efficiency

sharp drop in efficiency. By the 60th minute, efficiency dropped to about 0.5 for all designs. Between the 80th and 160th minute, efficiency tended to stabilize but was low, ranging from 0.3 to 0.8. Interestingly, at 180th minute, the Circular design showed an increase in efficiency to about 1.3, while the serpentine decreased to about 0.3, and the Parallel remained stable at around 0.6. Overall, the Circular design showed the most stable and efficient performance in the long run. Figure 11 shows that each pipe configuration has different cooling performance characteristics in maintaining thermal efficiency throughout the test period.

CONCLUSIONS

The research conclusion shows that circular pipe variation is the most effective method in reducing the PV surface temperature compared to other variations. The unmodified variation reached the highest temperature of around 67°C at the 80th minute, while the circular pipe variation managed to maintain the PV surface temperature at the lowest level, approximately 42°C at the same time. The serpentine and parallel pipe variations produced higher maximum temperatures, about 50°C and 45°C respectively. After the 80th minute, the temperature in all variations gradually decreased until the 180th minute, but the circular pipe continued to demonstrate the best performance in controlling the PV surface temperature. This study was limited to controlled indoor conditions without considering environmental factors such as wind, solar irradiance variation, humidity, and dust. Further research is needed to assess the system's performance and reliability under real outdoor environments for practical large-scale PV applications.

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DECLARATION OF CONFLICTING INTERESTS

The authors declare that they have no potential conflicts of interest regarding the research, authorship, and/or publication of this article.

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