Journal of Environmental and Development Studies - JEDS
Journal homepage: https://talenta.usu.ac.id/jeds

Experimental Study on the Effect of Zigzag Configuration of Paraffin Wax-Filled Aluminum Containers on the Thermal Performance of a Photovoltaic Thermal System

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ARTICLE INFO

Article history:
Received 08 July 2026
Revised 27 July 2026
Accepted 01 August 2026
Available online 01 September 2026

E-ISSN: 2745-4592

How to cite:
Putra S. J., Chandrasari A. Z., Rajani A. Experimental Study on the Effect of Zigzag Configuration of Paraffin Wax-Filled Aluminum Containers on the Thermal Performance of a Photovoltaic Thermal System. Journal of Environmental and Development Studies 2026. 7(2):001–008.

http://doi.org/10.32734/jeds.v7i2.26411

ABSTRACT

The performance of photovoltaic (PV) panels decreases significantly as operating temperatures rise. To mitigate this, forced-air cooling is often employed, but fluctuating outdoor solar radiation makes the integration of phase change materials (PCM) essential for effective heat regulation. This study experimentally evaluates the thermal performance of an air-based photovoltaic thermal (PV/T) system integrated with a zigzag arrangement of aluminum containers filled with paraffin wax PCM. The zigzag geometry was specifically designed to extend the contact path for forced convective heat transfer. Three PCM mass variations (150 g, 200 g, and 250 g) were tested outdoors in an urban environment from 09:00 to 15:00 WIB. The system's thermal response was monitored using K-type thermocouples, DHT22 sensors, and a solar power meter to record radiation intensity, component temperatures, and inlet-outlet air temperature differences (ΔT). Experimental results showed average solar irradiance values of 817.16, 643.76, and 606.05 W/m² for the 150 g, 200 g, and 250 g tests, respectively. The PV backsheet recorded the highest average temperatures across all setups, reaching up to 57.88°C. Notably, the 200 g PCM configuration demonstrated the optimal thermal response, achieving the highest peak PCM ΔT of 10.98°C at 13:00. Furthermore, the system yielded average positive air ΔT values of 6.37°C, 5.00°C, and 4.83°C for the respective masses. These findings confirm that forced air flow effectively removes heat from the zigzag PCM section, highlighting that selecting an appropriate PCM mass is critical for balancing heat absorption and continuous convective removal under dynamic field conditions.

Keywords: Air Cooling, Aluminium Container, Phase Change Material, Photovoltaic Thermal, Zigzag Configuration.

1. Introduction

Photovoltaic thermal (PV/T) is a hybrid solar energy system that combines photovoltaic modules with a thermal collector, enabling the simultaneous utilization of solar energy as electricity and heat. In an air-based PV/T system, the collector uses airflow as a heat-transfer medium, resulting in a relatively simple construction, low leakage risk, and suitability for flat-plate collector experiments in tropical environments (Farzan et al., 2025).

The performance of photovoltaic panels is highly influenced by the operating temperature, as an increase in cell temperature can reduce the electrical conversion efficiency. A portion of the solar radiation that is not converted into electrical energy turns into heat, consequently increasing the temperature of the backsheet and the space beneath the panel. Therefore, parameters such as radiation, collector area, inlet-outlet air temperatures, and air flow rate need to be evaluated together to assess the system's capability in transferring heat (Laghari et al., 2020; Chaibi et al., 2021).

Active cooling using forced airflow is employed to reduce the thermal load on the panels through convective heat transfer. However, outdoor testing is characterized by fluctuating radiation due to weather changes, causing the system's temperature response to vary over time. This condition makes heat storage media relevant in helping to retain and release heat more gradually (Boutina et al., 2024).

Phase change material (PCM) is used as a latent heat storage medium because it can absorb energy while undergoing a phase change within a specific temperature range. The integration of PCM in a PV/T system has been reported to help regulate module temperature and slow the temperature rise of components when radiation increases (Dayer et al., 2024; Hassan et al., 2020). In addition to the PCM type, the PCM mass also needs to be analyzed because mass differences can affect the heat storage capacity, the rate of temperature rise, and the heat release process during testing (Rajamony et al., 2024; Zaim & Farzan, 2021).

The testing in this study was conducted around the campus environment of Universitas Widyatama, Bandung. This location is maintained in the introduction as it serves as a field context explaining the actual testing conditions, namely an open area with direct solar radiation exposure between 09:00 and 15:00 WIB. Furthermore, the campus environment represents outdoor testing conditions in urban areas, allowing changes in radiation, temperature, and airflow to be analyzed as the system's thermal response to real field conditions.

Based on the aforementioned descriptions, this research investigates the effect of varying PCM masses of 150 g, 200 g, and 250 g on the thermal performance of an air-cooled PV/T system integrated with zigzag aluminum containers. The sought comparison is not merely identifying the largest PCM mass, but rather finding the configuration that produces the best thermal response based on solar radiation, component temperatures, PCM ΔT rise, and inlet-outlet air ΔT. Thus, the objective of this study is to evaluate the correlation among variations in PCM mass, daily radiation conditions, and the ability of forced air flow to carry heat out of the system.

2. Method

2.1 Experimental Setup and Testing Design

The system used is an air-cooled PV/T comprising a PV module, 6 mm glass, air channel space, zinc absorber, DC fan/blower, and zigzag-arranged aluminum containers. The aluminum containers were filled with paraffin wax with mass variations of 150 g, 200 g, and 250 g. The zigzag geometry was selected to extend the contact path among the air, PCM containers, and absorber plate, thereby increasing the heat transfer probability (Saberi et al., 2023; Aktas et al., 2019). This design was employed so that comparisons among PCM mass variations could be observed under the same flow path, making it easier to correlate thermal response differences with PCM mass and daily radiation conditions.

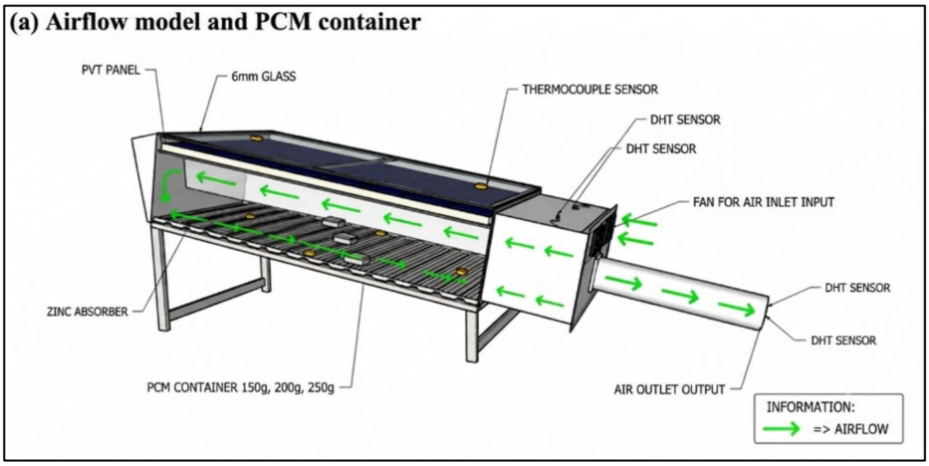

Figure 1. Air model and placement of PCM containers in the zigzag PV/T-PCM system

Table 1. Main specifications of the PV/T-PCM system

Parameter	Symbol	Value/Unit
Collector width	W	1.135 m
Collector length	L	2.285 m
Phase Change Material	PCM	Paraffin wax; 150 g, 200 g, 250 g
PV temperature coefficient	β	0.0035/°C
PV packing factor	PF	0.92
PV panel absorptivity	α	0.91
Glass emissivity	εg	0.90
PV panel emissivity	εpv	0.95
Insulation thermal conductivity	k	80

The specifications in Table 1 indicate that the system utilizes a collector measuring 1.135 m x 2.285 m. The paraffin wax PCM was placed in aluminum containers as a latent heat storage medium. Aluminum containers were chosen due to their simplicity, formability, and thermal conductivity, which support heat transfer to the PCM (Samykano, 2022; Wu et al., 2020). Furthermore, the collector dimensions and material characteristics serve as the basis for interpreting the experimental results, as they affect the contact area, heat absorption capacity, and temperature distribution in the space beneath the panel.

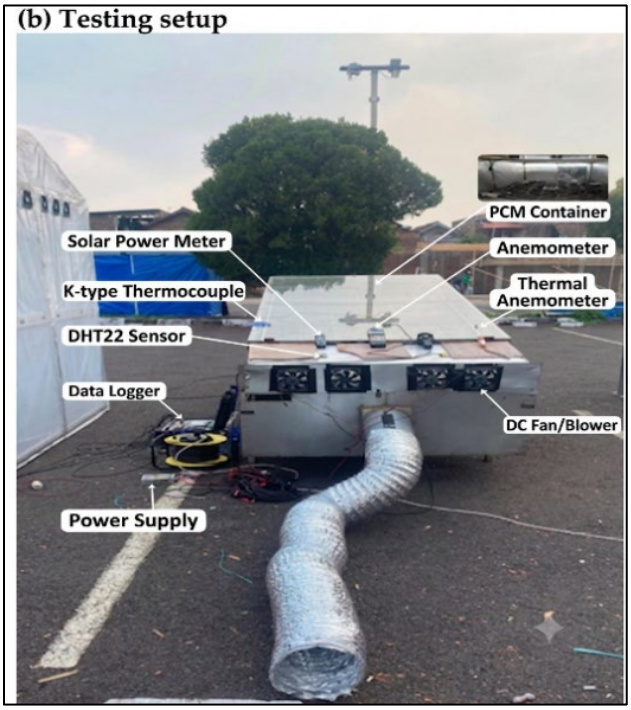

Figure 2. PV/T-PCM testing apparatus used around the Universitas Widyatama campus

Table 2. Description of the measuring instruments used

No	Instrument	Specification	Function
1	Data logger	Automatic recording every minute	Records sensor data continuously.
2	Solar Power Meter TM-750	Range 0-4000 W/m²	Measures solar radiation intensity.
3	K-type thermocouple	-40°C to 250°C; accuracy ±0.4%	Measures the temperatures of the panel, PCM, and absorber.
4	Anemometer	0-60 m/s; resolution 0.1 m/s	Measures ambient wind speed.
5	Thermal anemometer	0.1 m/s + 5% measured value	Measures outlet air flow rate.
6	DHT22	40°C-80°C; accuracy ±0.5°C	Measures inlet and outlet air temperatures.

The instruments in Table 2 were used to ensure the main parameters could be recorded during the testing. K-type thermocouples were utilized to measure the temperatures of the glass, PV backsheet, PCM, and zinc absorber. DHT22 sensors were placed at the air inlet and outlet sides, while a solar power meter was used as the basis for solar radiation readings.

2.2 Research Flowchart

The research flowchart in Figure 3 was enlarged to ensure each stage is clearly legible. The stages started from Start, literature study, preparation of tools and materials, PV/T system assembly, instrument calibration, field testing, PCM mass variations, data analysis, to Finish. This presentation helps demonstrate that the research process was conducted sequentially, from planning, data collection, and data processing to result interpretation.

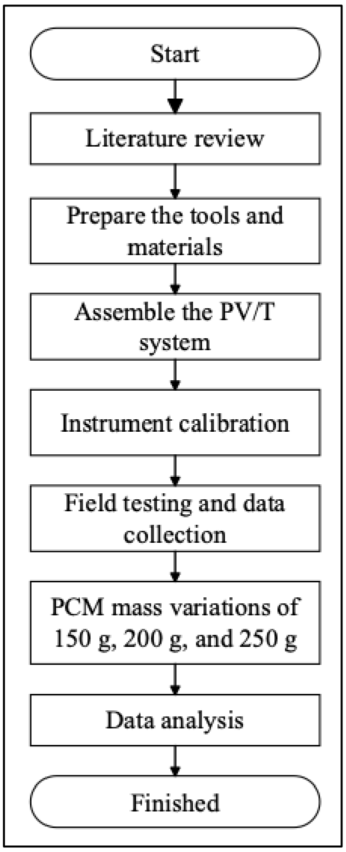

Figure 3. Flowchart of the PV/T-PCM research with zigzag aluminum container configuration.

2.3 Testing procedure and analytical parameters

Testing was conducted on three different days: 11 June, 2026 for 150 g PCM, 12 June, 2026 for 200 g PCM, and 15 June, 2026 for 250 g PCM. Data were recorded from 09:00 to 15:00 WIB. The recorded parameters included solar radiation, ambient wind speed, glass temperature, PV backsheet temperature, PCM temperature, absorber temperature, inlet air temperature, outlet air temperature, and outlet air flow rate.

The equations section is simplified to the core parameters directly used in the discussion. The equations for the air temperature difference and PCM temperature are utilized to interpret the heat transfer process from the collector to the air stream as well as the heat storage response of the PCM (Naghdbishi et al., 2022; Das et al., 2021). Calculations of latent heat capacity serve as a theoretical basis for explaining the relationship among PCM mass, radiation, and system output (Ata & Ozselcuk, 2025; Farzan et al., 2022). Meanwhile, the concepts of heat transfer and measurement uncertainty are used as references for interpreting the experimental results so that the data reading is not merely descriptive (Bergman et al., 2011; Kline & McClintock, 1953).

$$\Delta T_{air} = T_{out} - T_{in} \tag{1}$$

$$\Delta T_{PCM} = T_{PCM,t} - T_{PCM,0} \tag{2}$$

Where: ΔTair is the difference between the outlet and inlet air temperatures (°C), ΔTPCM is the increase in PCM temperature relative to the initial temperature (°C), G is the solar radiation intensity (W/m²), and Ac is the collector area (m²). These symbols are used to connect field measurement results with thermal performance indicators, ensuring the discussion not only presents graphs but also has a clear calculative foundation.

3. Result and Discussion

3.1 Comparative Solar Radiation Conditions

Figure 4 shows the solar radiation intensity during the testing of the three PCM mass variations. The graph is plotted as lines so that the changes in radiation from 09:00 to 15:00 WIB can be read more clearly. The bottom and left axis labels are given sufficient space to avoid being cut off in the document.

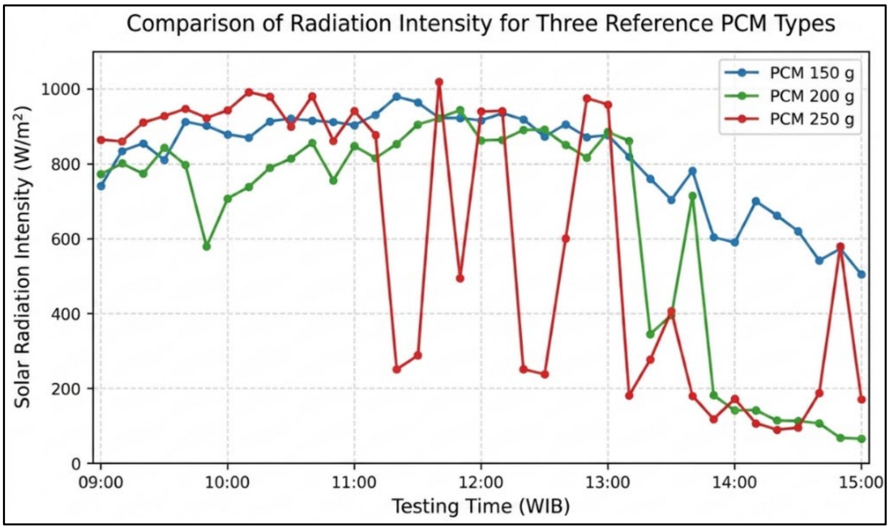

Figure 4. Comparison of comparative solar radiation intensity for 150 g, 200 g, and 250 g of PCM

Based on Figure 4, the average radiation value during the 150 g PCM test was 817.16 W/m², higher than the 200 g PCM at 643.76 W/m² and the 250 g PCM at 606.05 W/m². This difference needs to be noted in the discussion because the temperature response is influenced not only by the PCM mass, but also by the daily radiation conditions that fluctuate during outdoor experiments.

3.2 Comparison of PCM ΔT over time

Figure 5 illustrates the changes in PCM ΔT relative to the initial temperature of each test. The PCM ΔT value was calculated from the average temperature of the T5 and T6 sensors, representing the PCM temperature. This graph is used to evaluate the PCM's capability to absorb heat during the testing hours.

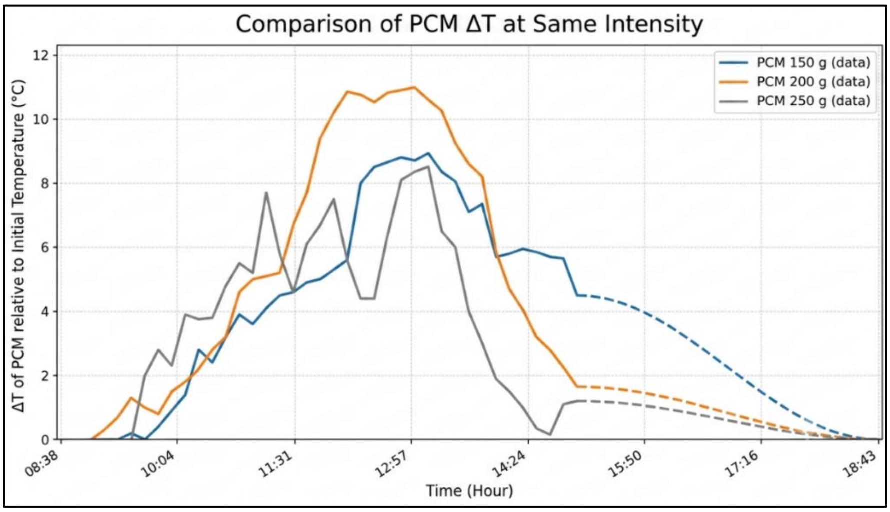

Figure 5. Comparison of PCM ΔT at similar intensities with predicted declines for 150 g, 200 g, and 250 g mass variations.

The peak PCM ΔT for the 150 g variation reached 8.93°C at 13:10, while the 200 g variation reached 10.98°C at 13:00. The 250 g variation produced a peak PCM ΔT of 8.51°C at 13:10. These results indicate that in the new data, the 200 g variation provided the highest PCM temperature rise response, showing that its heat absorption capability appeared to be the strongest under these testing conditions.

The trend in Figure 5 also shows that an increase in PCM mass does not always result in the highest ΔT when the daily solar radiation is not identical. For the 250 g variation, the PCM mass was greater, but the average radiation on the test day was lower than that of the 150 g. Therefore, interpreting the results requires considering the combination of PCM mass, radiation intensity, and heating duration.

3.2 Summary of component temperatures

Figure 6 summarizes the average temperatures of the main system components. The compared parameters include the temperatures of the glass, PV backsheet, PCM, absorber, inlet air, outlet air, and air ΔT. This comparison helps to identify which parts of the system dominantly experience heating.

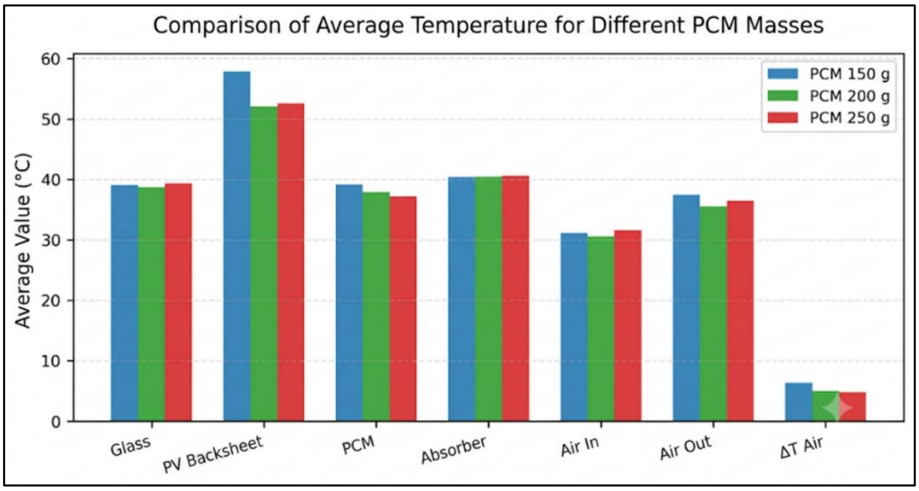

Figure 6. Comparison of average component temperatures and air ΔT across PCM mass variations.

The average PV backsheet temperature was the highest value across all variations, recording 57.88°C for 150 g PCM, 52.05°C for 200 g PCM, and 52.60°C for 250 g PCM. This indicates that the greatest amount of heat remains concentrated in the panel/backsheet area before being transferred to the aluminum containers, PCM, absorber, and air stream.

The obtained average air ΔT was 6.37°C for 150 g PCM, 5.00°C for 200 g PCM, and 4.83°C for 250 g PCM. The positive air ΔT values indicate that the forced air flow can extract heat from the space beneath the panel and carry it to the outlet. However, the 150 g variation produced the highest average air ΔT because its test day also had the highest average radiation.

3.3 Implications of PCM mass variations

Based on the radiation data, PCM ΔT, and component temperatures, the 200 g variation can be interpreted as the most responsive configuration in absorbing heat during this test because it produced the highest peak PCM ΔT of 10.98°C. A limitation of this outdoor study is the variation in daily weather, resulting in different average solar radiation levels (817.16 W/m² for 150 g, 643.76 W/m² for 200 g, and 606.05 W/m² for 250 g). However, the 200 g configuration is still considered the most optimal despite this discrepancy.

The 150 g variation was exposed to significantly higher radiation (817.16 W/m²) but produced a lower peak PCM ΔT (8.93°C), indicating that its thermal mass was insufficient to absorb the available heat maximally. Conversely, while the 250 g variation's lower response (8.51°C) was partly influenced by the lowest radiation conditions (606.05 W/m²), the 200 g setup demonstrated that even at moderate radiation (643.76 W/m²), it could achieve the most effective heat absorption (10.98°C). This indicates that the 200 g mass provides the most appropriate balance for thermal capacity and responsiveness under these system parameters. The 150 g variation exhibited the highest air ΔT, but this naturally coincided with its greater average radiation exposure. Meanwhile, the 250 g variation still demonstrated a heat absorption function, but the lower radiation conditions caused its thermal response to be lower than the other two variations.

Physically, a PCM with a larger mass has a higher heat storage capacity, but its temperature rise process is also influenced by incoming radiation, thermal contact area, container conductivity, and forced convection effectiveness. Therefore, the zigzag aluminum container system needs to be analyzed not only by the PCM mass but also by the uniformity of radiation and the distribution of airflow (Chandrasekar & Senthilkumar, 2021; El Kassar et al., 2025). This narrative clarifies that the research outcomes do not merely seek the largest PCM mass, but rather aim to find the most appropriate configuration based on the balance between heat absorption by the PCM and heat removal by the air flow.

4. Conclusions

This study demonstrates that an air-based PV/T system with zigzag aluminum containers filled with paraffin wax can be used as a thermal management medium for solar panels. Testing three PCM mass variations resulted in average radiation values of 817.16 W/m² for 150 g, 643.76 W/m² for 200 g, and 606.05 W/m² for 250 g. The PV backsheet temperature was the highest component temperature across all variations, indicating that the rear area of the panel remains the primary point of heat accumulation. The 200 g variation produced the largest peak PCM ΔT of 10.98°C, which indicates the strongest heat absorption response in this testing data. Meanwhile, the average air ΔT was positive across all variations, specifically 6.37°C, 5.00°C, and 4.83°C, proving that forced air flow is capable of carrying heat out of the system. Future studies need to equalize the radiation levels or employ a radiation normalization method so that the effect of PCM mass can be compared more precisely.

5. Acknowledgements

The authors would like to express their gratitude to the Mechanical Engineering Study Program of Universitas Widyatama, the National Research and Innovation Agency (BRIN), and all parties who assisted in the equipment design, sensor installation, data collection, and preparation of this article. This support played a crucial role in the smooth execution of the field-testing process and the compilation of the research results on the PV/T-PCM system based on zigzag aluminum containers.

6. Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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