

Optimizing PCM Mass in a Photovoltaic Thermal System

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ABSTRACT: The focus of this study is to analyze an air-cooled double-pass photovoltaic thermal (PV/T) system integrated with paraffin wax as a phase change material (PCM). The integration of Phase Change Material (PCM) is one of the most promising methods in PV/T thermal management. Paraffin wax PCM possesses a high latent heat of fusion, enabling it to absorb a significant amount of thermal energy at a relatively constant temperature during the solid-to-liquid phase transition process. The experiment was conducted over three days using three PCM mass variations (500 g, 1000 g, and 2000 g). To ensure an objective data comparison, measurements were adjusted to identical solar radiation intensities. The experimental setup comprised a PV module, 6 mm glass cover, air ducting, reflector/absorber plate, PCM container, type-K thermocouples, DHT22 sensors, a solar power meter, an anemometer, a Testo 405i, and a data logger. The experimental results recorded average air temperature differences ΔT of 6.74°C (500 g PCM), 6.72°C (1000 g PCM), and 6.91°C (2000 g PCM). Increasing the amount of PCM resulted in a reduction in the average reflector temperature from 44.97°C to 43.45°C, demonstrating the critical role of PCM mass in dampening system heat spikes.

KEYWORDS: Data logger; paraffin wax; phase change material; photovoltaic thermal; solar radiation.

I. INTRODUCTION

Photovoltaic thermal (PV/T) systems seamlessly integrate the simultaneous conversion of solar radiation into electrical energy within photovoltaic modules with the effective harvesting of excess thermal energy accumulated across the panel surface using a dedicated working fluid. In comparison to liquid-cooled configurations, air-based PV/T systems have increasingly emerged as a primary focal point in thermal management research, owing to their lower structural complexity, operational reliability, and seamless integration onto conventional flat-plate collectors [1].

Elevated operating temperatures constitute a major technological hurdle in optimizing the performance, reliability, and longevity of photovoltaic thermal (PV/T) collector systems. This thermal degradation occurs because only a fraction of incoming solar radiation is successfully converted into usable electrical energy, while the remaining unabsorbed and unconverted energy dissipates as waste heat within the semiconductor layers. The continuous build-up of this surplus thermal energy on both the front and rear faces of the module drives-up its operational temperature, directly leading to a decrease in electrical output and overall system efficiency. Therefore, integrating an efficient and continuous heat dissipation mechanism is essential to control thermal accumulation, maintain optimal operating temperatures, and prevent thermal overloading of the PV module [2].

Within the operational framework of air-cooled PV/T systems, thermal dissipation from the rear surface of the photovoltaic module relies on directing forced or natural airflow through internal flow channels toward the discharge outlet. This moving air stream serves as the primary heat transfer medium, continuously sweeping away excess thermal energy to mitigate localized overheating and stabilize overall system performance. According to heat transfer theory applicable to solar collectors, the overall heat collection efficiency is intrinsically linked to key environmental and physical parameters, such as the level of solar radiation intensity, the total surface dimensions of the collector, the volumetric airflow rate or velocity, and the dynamic temperature difference developed between the incoming inlet air and outgoing exhaust air [3].

In addition to active cooling via forced or natural airflow, passive thermal management strategies can be seamlessly integrated into the system through the incorporation of Phase Change Materials (PCMs). PCMs possess the unique ability to buffer and suppress rapid system temperature increases by absorbing substantial amounts of latent heat at a relatively constant temperature during their phase transition process. In PV/T applications, PCMs are typically installed on the rear side of the photovoltaic module or embedded around the absorber plate surface to temporarily store excess thermal energy that has not yet

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been extracted by the primary airflow [4], [5]. To further augment thermal dissipation, PCM utilization is frequently combined with complementary cooling techniques, such as forced-air convection and double-pass collector ducting configurations. Nevertheless, optimizing the PCM mass remains a critical design parameter that demands rigorous analysis, as both the total thermal storage capacity and the transient heat release dynamics are intrinsically dictated by the specific quantity of the phase change medium employed [6].

Although numerous studies have successfully demonstrated the efficacy of Phase Change Materials (PCMs) in optimizing the thermal performance and operational stability of photovoltaic thermal (PV/T) systems, the vast majority of existing literature remains heavily focused on evaluating different types of PCM, novel collector structural configurations, or alternative cooling techniques. Consequently, research specifically addressing the thermal impact of PCM mass variation within an air-cooled doublepass PV/T architecture under normalized solar irradiance conditions remains surprisingly scarce. Nevertheless, gaining a comprehensive understanding of how system thermal responses scale with varying PCM masses is of paramount importance, serving as a fundamental prerequisite for determining the precise material quantity required for practical and cost-effective airbased PV/T implementations [7].

Driven by this critical imperative, this study was conducted to comprehensively analyze the impact of varying PCM mass loads (specifically paraffin wax at 500 g, 1000 g, and 2000 g) on the thermal performance of an air-cooled double-pass photovoltaic thermal (PV/T) system. The PCM material was strategically positioned beneath the panel assembly, adjacent to the absorber/reflector plate, to absorb and temporarily store excess thermal energy before gradually discharging it into the cooling air stream. The implementation of a double-pass ducting architecture was designed to extend the fluid flow path, thereby enhancing heat transfer effectiveness between the system components and the circulating air. Crucially, the thermal evaluations were carried out under normalized solar irradiance conditions across all mass variations, ensuring that observed differences in thermal response strictly represent the distinct effect of PCM mass addition rather than ambient radiation fluctuations. The findings derived from this investigation are expected to contribute significantly to the technological development of air-based PV/T systems while serving as a rigorous scientific benchmark for determining optimal PCM sizing in practical solar applications.

II. METHODOLOGY

Experimental Apparatus Configuration and Testing Design

This experimental investigation utilizes an air-cooled double-pass photovoltaic thermal integrated with phase change material (PV/T-PCM) configuration. The PV module is positioned at the top of the assembly and fitted with a 6 mm protective glass cover, which serves a dual purpose: acting as a physical shield and creating a thermal trapping cavity to minimize top thermal losses. The lower section of the unit houses the air ducting network, a combined reflector/absorber plate, and dedicated PCM containers. Cooling air is continuously drawn into the system by an inlet fan, traversing the first flow channel directly beneath the PV module. The air stream then reverses direction into the second pass, flowing across the PCM containers and the absorber plate before being discharged through the exhaust outlet. This double-pass architecture is specifically implemented to extend both the air residence time and the flow contact trajectory, which effectively enhances convective heat transfer efficiency across the solar collector [9], [10].

The schematic and physical visualization of the upgraded double-pass PV/T-PCM experimental test rig is presented in Figure 1. Figure 1(a) illustrates the actual physical experimental setup, complete with the spatial layout of the airflow direction, the bifacial PV module, the data logger, and primary measuring instruments such as DHT22 sensors and type-K thermocouples. Meanwhile, Figure 1(b) reveals the internal structural architecture of the collector, which accommodates the PCM containers and the reflector plate. The spatial arrangement of these sensors is explicitly depicted to provide a clear and comprehensive overview regarding the exact data acquisition points for air, surface, and PCM zone temperatures.

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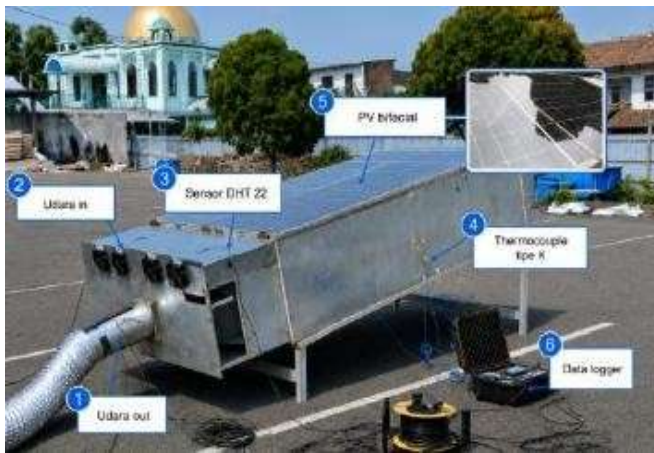


Fig.1(a) Experimental Setup and Sensor Placement



Fig.1 (b) PCM Container and Reflector

The instrumentation configuration detailed in Table 1 was meticulously designed to ensure high precision and consistency in recording all thermal variables and ambient environmental conditions. Air temperature measurements at both the inlet and outlet sections are conducted using DHT22 sensors. Meanwhile, K-type thermocouples are strategically installed at several critical thermal nodes, including the protective glass cover, the PV module backsheet, the reflector/absorber plate, and within the PCM thermal zone. Incident solar irradiance levels are strictly normalized and monitored based on real-time readings from a calibrated solar power meter, while airflow characteristics and velocity profiles across the ducting system are continuously monitored using a digital anemometer alongside a Testo 405i thermal anemometer.

Table 1. Sensor specifications

No	Tools	Specification
1	DHT22	-40 ~ 80 °C
2	Thermocouple type-K	~ 250 °C
3	Data Logger	Data Acquisition (DAQ) System
4	PCM	Paraffin wax
5	Solar power meter	0 ~ 1800 W/m ²
6	Anemometer	0 ~ 30 m/s
7	Testo 405i	To measure the airflow velocity at the outlet channel.

A detailed schematic diagram of the double-pass PV/T-PCM system model investigated in this research is depicted in Figure 2. The bifacial photovoltaic module is situated between a 6 mm thick protective glass cover and an underlying reflector plate. With this structural configuration, forced air induced by the intake fan first moves along the primary upper duct—the enclosed space bounded by the glass cover and the upper surface of the PV module. Upon reaching the terminal end of the solar collector, the air stream reverses its direction in a distinct U-turn trajectory to navigate through the secondary lower channel, sweeping past the reflector surface and the integrated PCM containment matrix prior to being exhausted through the outlet duct.

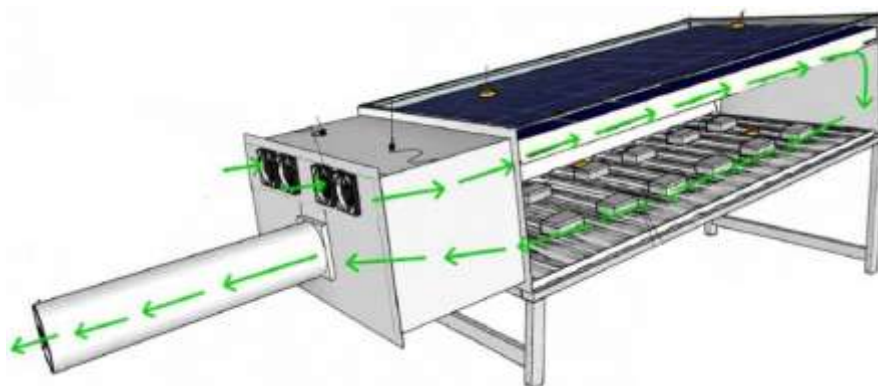


Fig 2. Double-pass PV/T-PCM model and system airflow direction

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Table 2. Specifications The bifacial photovoltaic module

No	Tools	Specification
1	Module PV	PV bifacial monocrystalline 540 Wp
2	Frame	Aluminum
3	PCM	Paraffin wax (500 g, 1000 g, 2000 g)
4	Container PCM	Stainless Steel
5	Absorber/reflector	Aluminum foil
6	Air Duct	Galvanis
7	Fan	DC 12 volt

A detailed breakdown of the key materials comprising the PV/T-PCM system architecture is summarized in Table 2. The photovoltaic module operates to capture incident solar irradiance while concurrently producing electrical energy, while the integrated air channels function as dedicated pathways for convective heat transfer. Within the lower enclosure beneath the module, a dual-purpose reflector/absorber plate is deployed to substantially enlarge the thermal contact boundary. Furthermore, the PCM containment units are arranged in a parallel configuration to maximize the efficiency of gradual heat absorption and latent heat release. The decision to employ a rectangular enclosure for the PCM casing is justified by its simple geometric configuration, straightforward manufacturing process, and extensive implementation across flat-plate collector-based thermal storage applications [11]–[14].

III. RESULT AND DISCUSSION

a) Solar Radiation

Figure 3 presents a comparison of solar radiation intensity, which serves as a baseline reference across the three PCM mass variations. The employment of measurement data-driven line charts facilitates the visualization of dynamic changes in radiation intensity from the beginning to the end of the testing period. Additionally, the label sizes on the horizontal axis (representing time) and vertical axis (representing intensity) were adjusted, alongside the inclusion of margin padding, to guarantee visual legibility without truncating any portion of the graphical representation.

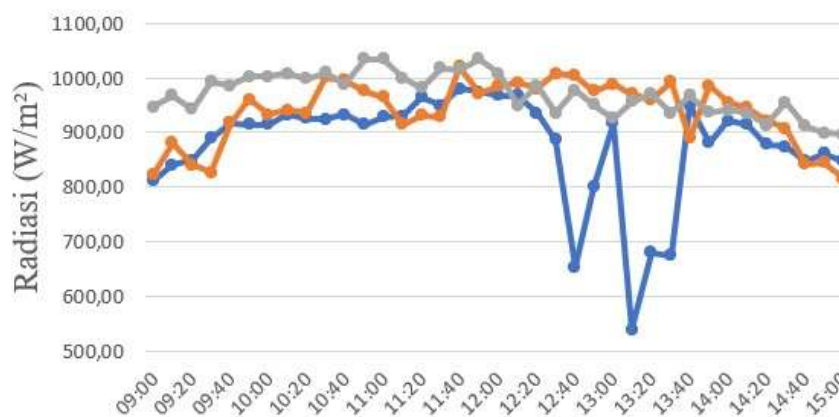


Fig 3. Solar Radiasi

Figure 5 demonstrates that the solar irradiance distribution across all three experimental variations remains within a highly comparable intensity range. Employing a line chart format streamlines the tracking of temporal data trends, given that each measurement interval presents the corresponding readings for the three PCM variations side by side. This comparative presentation strategy effectively minimizes potential biases stemming from daily weather fluctuations, thereby establishing a firm foundation of solar radiation parity before undertaking the detailed temperature evaluation.

b) Temperature PCM (ΔT)

The progressive temperature rise within the PCM enclosure demonstrates that thermal energy derived from the PV module was effectively transmitted to the PCM containment matrix through conduction mechanisms. With the escalation of solar irradiance, the total heat absorbed by the PV panel increases, thereby driving a corresponding temperature rise in the PCM container. At the peak thermal period, the rate of temperature escalation begins to decelerate, signifying that a substantial fraction

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of the incoming thermal energy is being absorbed by the PCM as latent heat during its phase change transition. This thermal buffering mechanism suppresses drastic temperature spikes in the PCM container despite sustained high levels of solar radiation.

As the experiment approached its conclusion, the PCM container temperatures for all tested mass variations experienced a steady decline, settling around 41.00 °C by 15:00 WIB. This downward trend is directly attributable to the reduction in solar radiation intensity, which proportionally diminished the overall thermal energy input received by the system.

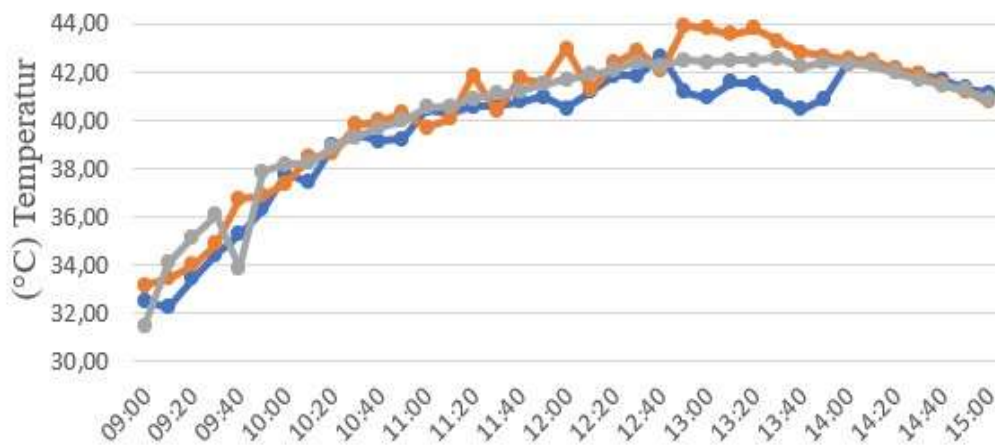


Fig 4. Temperature PCM

c) Correlation between PCM ΔT and solar irradiance

The relationship between PCM ΔT and solar radiation intensity is presented more objectively in Figure 5. The refinement of the graph was accomplished by standardizing the X-axis parameter at solar irradiance values of 850, 900, 950, and 1000 W/m². At each specified intensity level, three comparative bars represent the PCM mass configurations of 500 g, 1000 g, and 2000 g, thereby ensuring that the comparative evaluation is conducted under standardized irradiance conditions rather than relying on differing average radiation values.

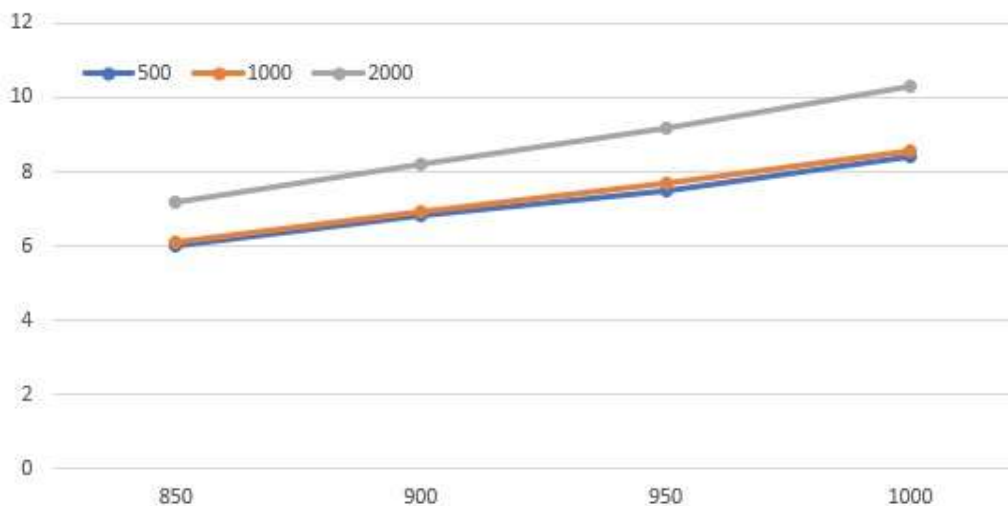


Fig 5. Correlation Between PCM ΔT and solar irradiance

As presented in Figure 5, the magnitude of PCM ΔT increases progressively alongside the elevation of solar radiation intensity from 850 W/m² to 1000 W/m². Across all evaluated solar irradiance thresholds, the 2000 g PCM configuration consistently achieves the maximum PCM ΔT relative to the 500 g and 1000 g mass variations. This result substantiates that a higher PCM mass accumulation yields a greater thermal storage potential, which enhances the system's ability to capture and retain thermal energy under uniform irradiance conditions. This observed behavior corroborates the findings of Khodadadi and Fan [20], who highlighted that augmenting thermal storage capacity facilitates superior heat uptake during the transient heating process. As a result, the larger PCM mass effectively stabilizes the thermal response of the system when exposed to identical radiation levels. d) Result

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The experimental results recorded relatively close average air ΔT values across variations, specifically 6.74 °C for 500 g PCM, 6.72 °C for 1000 g PCM, and 6.91 °C for 2000 g PCM. This demonstrates the effectiveness of air circulation in absorbing thermal energy within the under-panel cavity across all PCM mass quantities. The highest temperature rise observed in the 2000 g variation indicates that the thermal energy stored in the PCM can be released into the airflow progressively. Although the increase in air ΔT is relatively modest, the addition of PCM mass is proven to serve primarily as a heat storage medium rather than a direct driver of elevated outlet air temperatures. In other words, thermal energy is first absorbed by the PCM before being continuously transferred to the cooling air stream.

IV. CONCLUSIONS

1. System Composition and Instrumentation Layout.

The PV/T-PCM system is constructed from a set of primary components, including a PV module, a 6 mm protective glass cover, double-pass air ducting, an inlet fan, an outlet duct, a reflector/absorber plate, PCM containers, environmental instrumentation, and a data logger. Temperature measurements across the glass cover, PV backsheet, reflector/absorber plate, and PCM region were performed using K-type thermocouples, whereas air temperature monitoring at the inlet and outlet sides utilized DHT22 sensors.

2. PCM Thermal Characteristics and Statistical

Evaluation the 3000 g PCM configuration achieved the highest average ΔT PCM at 8.73 °C, demonstrating a more gradual thermal discharge behavior than the 500 g and 1000 g mass variations. Nevertheless, statistical analysis reveals that the numerical differences observed among the three test groups do not reach a level of statistical significance.

3. The Role of PCM as a Heat Buffer

An increase in PCM mass quantity is proven to suppress the average temperature of the reflector plate, decreasing from 44.97 °C in the 500 g PCM variation to 43.45 °C in the 2000 g PCM variation. This reduction underscores that the 2000 g PCM provides the most effective heat buffering effect within the lower compartment beneath the panel.

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