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# Experimental Study of Test Room Air Conditioning Using Solar Cold Energy Storage

Himsar Ambarita*[1], Albert Goldwin[1,2], Samar[1]

[1]*Sustainable Energy Research Centre, Faculty of Engineering, Universitas Sumatera Utara, Medan, 20155, Indonesia.*
[2]*Mechanical Engineering Department, Faculty of Engineering, Universitas Sumatera Utara, Medan, 20155, Indonesia.*

*Corresponding Author: himsar@usu.ac.id

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**ABSTRACT**

In tropical regions, air-conditioning systems are among the main contributors to building energy consumption, and their energy demand may account for more than half of the total building load. Therefore, improving cooling efficiency has become an important issue in current building energy management. This study experimentally investigates a solar-powered room cooling system using cold energy storage to reduce the air temperature in a test room with dimensions of 4.8 m × 3.7 m × 3.3 m. The proposed cooling unit combines thermoelectric cooling technology with an actively operated phase change material as the cold storage medium. In this active configuration, heat exchange between the indoor air and the PCM is enhanced through forced convection supported by additional mechanical components. The experimental results show that the system was able to lower the indoor air temperature to 26.75 °C and achieve a relative humidity of 58% when the average outdoor temperature was 29.55 °C. The maximum coefficient of performance of the CES system reached 0.7, with an average value of 0.39 during the first day of operation.

**Keywords:** cold energy storage, solar cooling

## 1. Introduction

In tropical regions, building cooling systems require a substantial amount of energy because they must continuously remove both sensible and latent heat from indoor spaces. As a result, HVAC systems may account for more than half of the total energy consumption in buildings [1]. This condition highlights the need for alternative cooling strategies that are more energy-efficient and suitable for tropical climates. One potential approach is the application of thermal energy storage (TES), which stores thermal energy by heating or cooling a medium so that the stored energy can be used later for heating or cooling purposes [2][3][4]. Among the available TES technologies, systems that store hot or cold energy within the temperature range of approximately -50°C to 120°C have strong application potential when combined with phase change materials (PCM) [5][6]. When PCM is used as latent heat thermal energy storage (LTHES) for cold energy storage (CES), it can serve as an alternative support system for conventional cooling because of its ability to store a large amount of thermal energy near its phase-change temperature and maintain relatively stable thermal behavior during charging and discharging processes [7]. The application of PCM in buildings can be carried out through passive or active systems [8]. In active systems, heat transfer between the PCM and indoor air is mainly supported by forced convection, which requires additional mechanical or electrical components to circulate air and improve thermal exchange [9]. PCM-based cold energy storage can also be combined with thermoelectric cooling technology. A thermoelectric module is a solid-state device that can convert electrical energy into heat transfer, making it suitable for compact cooling applications [10]. Thermoelectric cooling has several advantages, including small size, light weight, high reliability, quiet operation due to the absence of moving mechanical parts, and environmental friendliness because it does not require refrigerant. In addition, thermoelectric cooling operates using direct current, making it easier to integrate with photovoltaic panels as a renewable energy source [11]. Based on these considerations, this study applies a solar cold energy storage system as an experimental cooling device for a test room. The system uses photovoltaic panels as the power source and combines thermoelectric cooling with PCM as the cold energy storage medium. The study focuses on evaluating the effect of the system on indoor air temperature distribution and relative humidity in the test room.

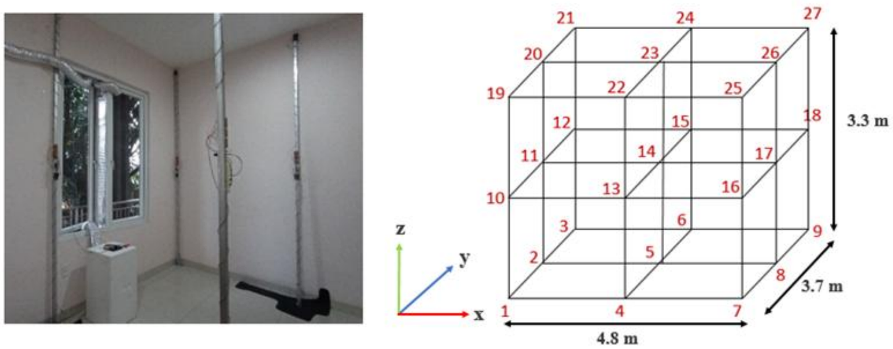
## 2. Method

The experimental equipment, test room configuration, and cooling system arrangement used in this study are explained in the following subsections.

### 2.1 System Description

This study was conducted in a test room located in Medan, North Sumatra. The room had dimensions of 4.8 m in length, 3.7 m in width, and 3.3 m in height, and was used as the experimental space for evaluating an air-conditioning system based on solar cold energy storage. The physical condition of the test room, including its geometry, wall position, window location, and sensor arrangement, is presented in Figure 1. Figure 1(a) shows the experimental setup of the test room, while Figure 1(b) illustrates the schematic representation of the room. In the schematic layout, sensor 1 was positioned at the reference coordinate point (0, 0, 0). Based on this coordinate system, the xz plane at y = 3.7 m represents the wall side of the test room where the window is located.

The solar cold energy storage unit used in this experiment was placed inside a styrofoam box with dimensions of 74 cm × 41 cm × 31 cm. As shown in Figure 2, the cooling unit consisted of four thermoelectric modules as the main cooling source, ice gel PCM as the cold energy storage medium, and six DC fans measuring 8 cm × 8 cm to support air circulation between the cooling unit and the test room. Four fans were installed on the outlet side of the styrofoam box to distribute cooled air into the room, while two other fans were installed on the inlet side to draw indoor air back into the cooling unit. The electrical power required to operate the cooling system was supplied by solar panels. The cooling box was designed with three air openings, consisting of two inlet openings and one outlet opening, to allow continuous air circulation during the experiment.




(a) (b)

**Figure 1.** Test room (a) experimental setup, (b) schematic representation of the test room

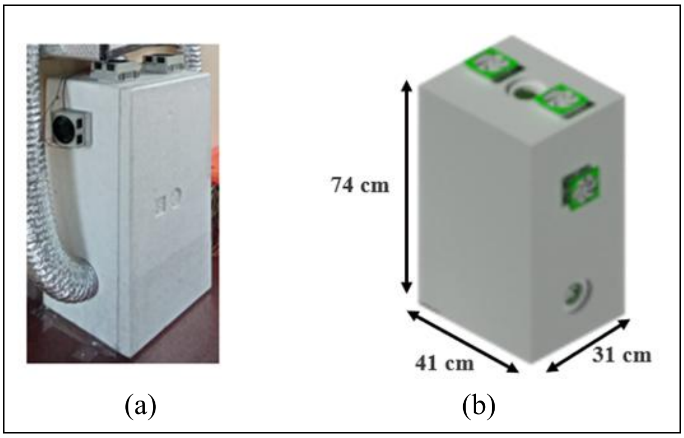



**Figure 2.** Solar cold energy storage (a) experimental setup, (b) schematic representation of solar cold energy storage

2.2 Procedure

The experiment was arranged under three operating conditions to evaluate and compare the performance of the cooling system. The first condition, Mode 1, was conducted in the test room without any cooling system and was used as the reference condition. The second condition, Mode 2, used a thermoelectric cooling system in the test room. The third condition, Mode 3, applied a solar cold energy storage system, which combined the thermoelectric cooling system with phase change material.

The experimental tests were carried out in the same test room on different dates. Mode 1 was tested on 12–13 August 2021, Mode 2 on 02–03 October 2021, and Mode 3 on 11–12 January 2022. As shown in Figure 3, solar panels were used as the main power source for operating the cooling device. Since the electrical output from the solar panels depends on solar radiation and may fluctuate during operation, a buck converter was installed to regulate the voltage supplied to the cooling system. The voltage was adjusted to a maximum of 12 V to match the working voltage of the system and to prevent damage to the electrical components. In this experimental configuration, the solar cold energy storage system consisted of thermoelectric modules and PCM installed inside the cooling unit.

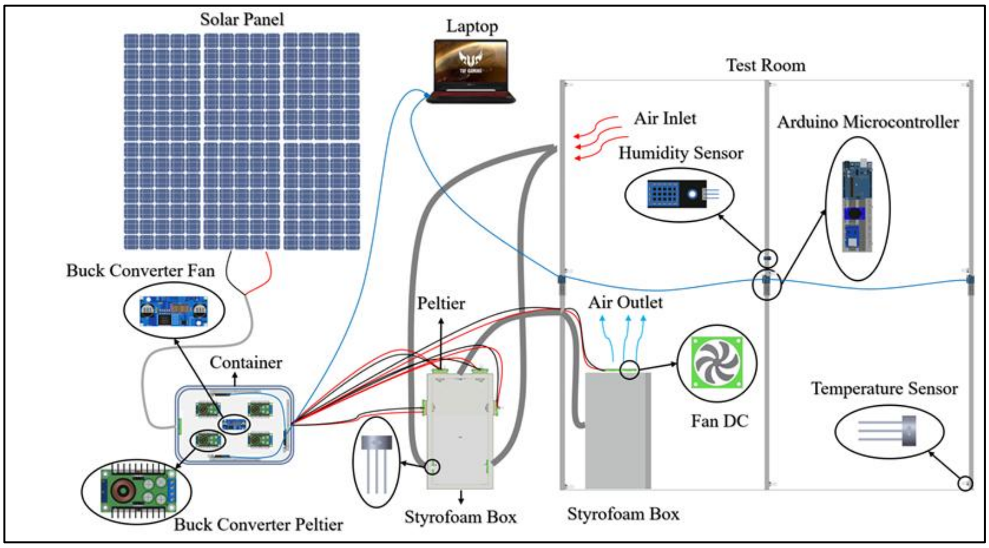



**Figure 3.** Experimental setup

The cooling process began when warm indoor air from the upper part of the test room was drawn into the cooler box. Inside the cooling unit, heat from the incoming air was absorbed by the thermoelectric cooling system and PCM. The cooled air was then supplied back into the test room with the assistance of DC fans, producing air with a lower temperature and supporting air circulation within the room. During the experiment, the voltage generated by the solar panels was monitored in real time using an Arduino microcontroller. The system was operated without battery storage; therefore, all tests were conducted from 08:00 AM to 05:00 PM, when sunlight was available to supply the solar panels. Before the cooling system was activated, the voltage was first regulated using the buck converter so that the supplied voltage did not exceed 12 V.

Air temperature in the test room was measured using temperature sensors placed at 27 different points, as illustrated in Figure 1. The sensors were positioned at three different heights, namely 0 cm, 165 cm, and 330 cm above the floor level. The temperature data collected from these points were then processed using Matlab software to visualize the indoor air temperature distribution in a 5D chart. Relative humidity was measured using a humidity sensor installed at the center of the test room, specifically at point 14 in Figure 1b. Additional temperature sensors were also installed on the six outer sides of the test room to compare the recorded temperature values between indoor and surrounding conditions. In the CES cooling unit, temperature sensors were placed at the inlet and outlet openings to measure the air temperature before and after passing through the cooling system.

2.3 Equation Used

Comparing the work of a cooling system, means talking about the coefficient of performance (COP). From the air side, the cooling capacity ($Q_c$) and COP of the refrigeration unit can be evaluated by the following equation:

$$Q_c = c_{p,air}\dot{m}\left(T_{in,air} - T_{out,air}\right) \tag{1}$$

Where $\dot{m}$ is the mass flow rate of air from the refrigeration unit, $T_{in,air}$ and $T_{out,air}$ are the inlet and outlet temperatures of the air flow through the cooling unit. $c_{p,air}$ is the heat capacity of the air passing through the cooling unit which is taken at the average temperature of $T_{in,air}$ and $T_{out,air}$.

$$COP_{unit} = \frac{Q_c}{P_{unit}} \tag{2}$$

Where $Q_c$ is the cooling capacity generated from the cooling unit and $P_{unit}$ is the total electrical power consumed by the thermoelectric and DC fans. For the DC fan work function equation used:

$$v = -0{,}0184V^2 + 0{,}4636V - 0{,}7807 \tag{3}$$

Where v is the speed of the DC fan and V is the voltage supplied to the DC fan. The equation was acquired from the graph in Fig. 4.

2.4 Tools and Materials Used

The measuring instruments for the experiment and the specifications are given in Table 1.

**Table 1**. Measuring equipment specifications

| **Equipment** | **Model** | **Range** | **Accuracy/resolution** |
|---|---|---|---|
| Temperature Sensor | DS18B20 | -55 +125 ℃ | ± 0,5 ℃ |
| Humidity Sensor | DHT11 | 20 – 90% RH | ±5% RH |
| Anemometer | GT8907 | 0 – 45m/s | ± 3%. |
| Voltage Sensor | - | 0 – 25 V | 0,00489 V |

The Peltier module used is the "TEC-12706" peltier module with specifications that can be seen in Table 2.

**Table 2.** Peltier module specification "TEC1-12706"

| Parameter | Hot Side Temperature (°C) | |
|---|---|---|
| | **25°C** | **50°C** |
| Q*max* (Watts) | 50 | 57 |
| Delta T*max* (°C) | 66 | 75 |
| I*max* (Amps) | 6.4 | 6.4 |
| V*max*(Volts) | 14.4 | 16.4 |
| Module Resistance | 1.98 | 2.3 |

The DC fans used in the experiment have dimensions of 8 cm x 8 cm x 2.5 cm with power of 2.6 W each fan. For the DC fan function graph in Fig. 4, the Exp data points were obtained through measurements using an anemometer in the voltage range of 2-12 V with 0.5 V increments. While the Eq curve is the result of polynomial regression of the Exp data points from which equation (3) is derived.

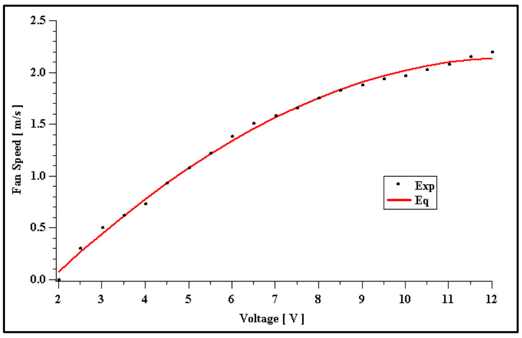



**Figure 4.** DC fan work function graph

The solar panels used in the experiment have a peak power output of 120 W (120 Wp). There were 6 solar panels in parallel configuration used to power the cooling system. The required amount of solar panels needed was 4 by calculation but 6 panels were used to ensure the availability of electrical power.

The PCM used in the experiment is ice gel contained in 24 plastic containers with volume of 400 ml each. The thermophysical properties of ice gel can be seen in Table 3 [12].

**Table 3.** Thermophysical properties of ice gel

| Properties | Values |
|---|---|
| Melting temperature | -5 °C |
| Freezing temperature | -5 °C |
| latent heat | 507952 J/kg |
| Liquid specific heat | 4024 J/kg °C |
| Solid specific heat | 1787 J/kg °C |
| Density | 1000 kg/m$^3$ |
| Liquid thermal conductivity | 0.55677 W/m K @20 °C |
| Solid thermal conductivity | 1.96 W/m K @-5 °C |

## 3. Result and Discussion

Experimental study for the cooling system was conducted in Medan, North Sumatra. The experiment was conducted to study the performance characteristics of the cooling system and the effect of the cooling system on the air temperature and relative humidity of the test room.

The test data from the arrangement of 27 sensors in the test room was visualized in 5D graph using Matlab software to show the temperature distribution of the test room in mode 1, where the temperature of the test room without was measured, mode 2, where the temperature the test room with thermoelectric cooler (without PCM) inside was measured, and mode 3, where the tempeature of the test room with thermoelectric cooler (with PCM) inside was measured as shown in Fig. 6.

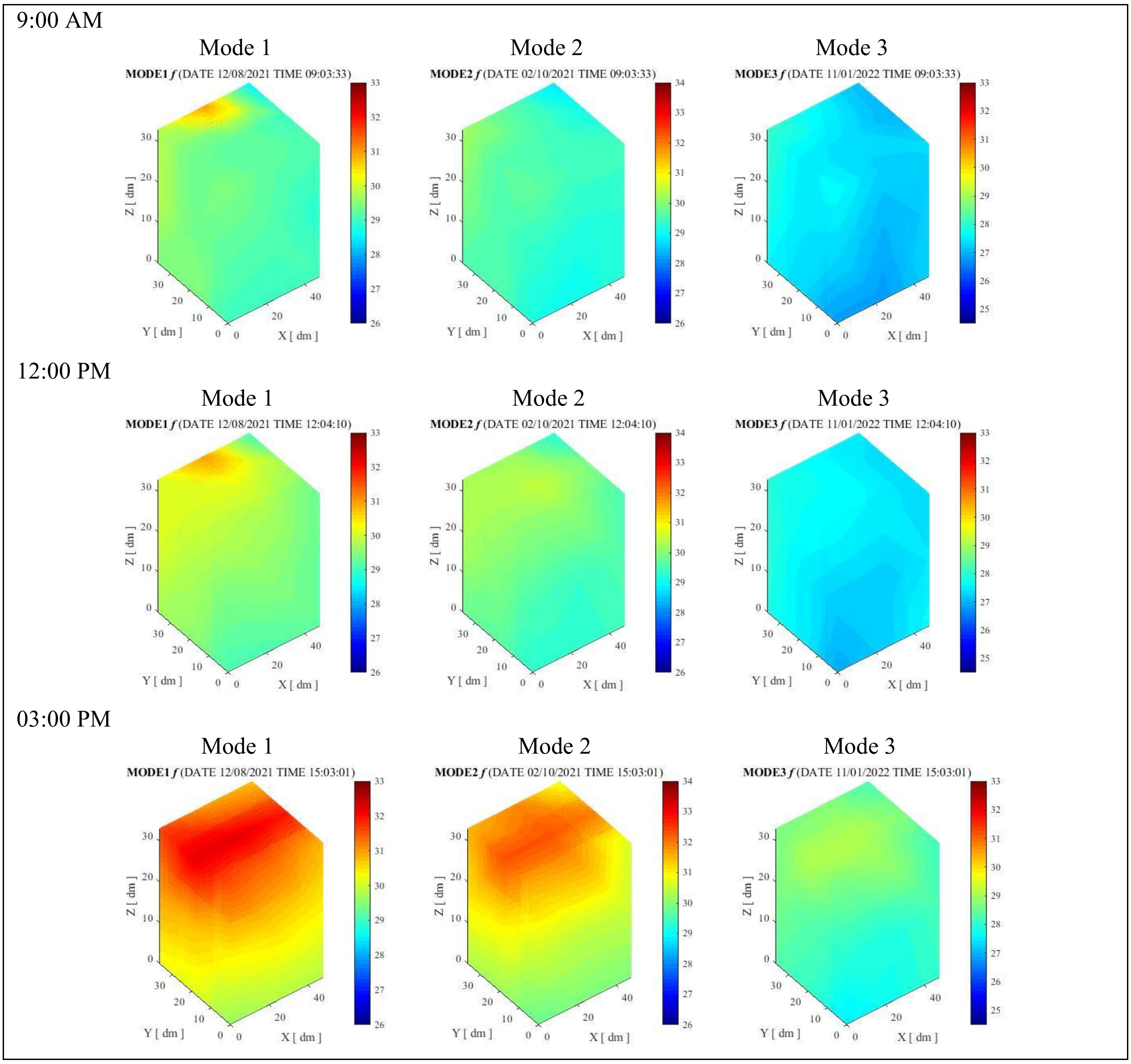



**Figure 5.** Air temperature distribution of the test room

It can be seen in Fig. 5 that the cooling system affects the air temperature of the test room by reducing fluctuations in the temperature in the room. It can be concluded that the most even distribution of room air temperature at 03:00 PM or after 7 hours of testing was in mode 3 experiment where in mode 1 experiment the temperature difference between the upper and lower part of the test room was 1.5°C, in mode 2 experiment the temperature difference between the upper and lower part of the test room was 1.2°C, while in mode 3 experiment the temperature difference between the upper and lower part of the test room was 0.6°C. It can be seen in mode 1 experiment from 9:00 AM to 12:00 PM that the air temperature in the area around the window appeared to be higher due to exposure to sunlight and the absence of air circulation in the room. The operation of the cooling system in the room in mode 2 and mode 3 experiments gave the effect of a more even distribution of air temperature.

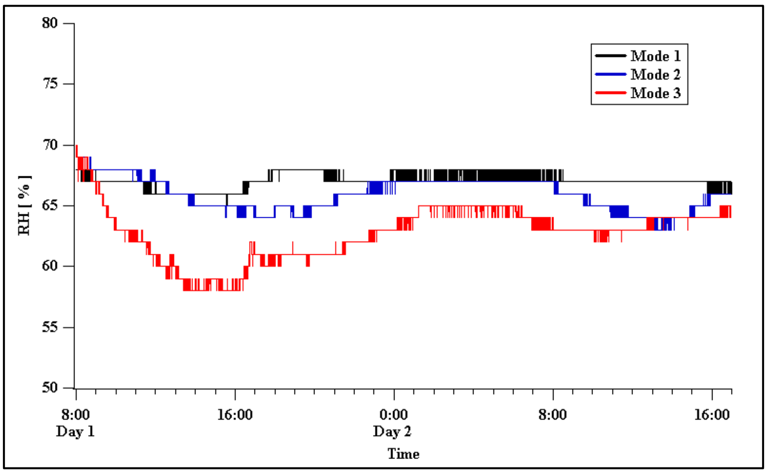



**Figure 6.** Relative humidity of the test room

It can be seen in Fig. 6 that in those 2 days of mode 1 experiment the humidity value of the test room was quite stable in the value range of 66-68%. On the first day of mode 2 experiment, the humidity in the test room started with a value of 69% then decreased to 64% at 03:30 PM and slowly increased again when the cooler stopped operating at 05:00 PM. Continued on the second day (starting at 8:00 AM) the humidity of the test room started with a value of 67% then decreased to 63% at 13:00 and remained at a value of 63-64% for 4 hours of testing. On the first day of mode 3 experiment, the humidity of the test room started with a value of 70% then decreased rapidly to reach 58% at 01:30 PM and increased again when the cooler stops operating at 05:00 PM. Continued on the second day (starting at 8:00 PM) the humidity of the test room started with a value of 64% then decreased to 62% and remained at a value of 62-63% for 5 hours of experiment. The decrease in relative humidity in the mode 2 experiment was caused by the condensation process on the coldsink of the thermoelectric system and the larger decrease in relative humidity in the mode 3 experiment was caused by an additional condensation process on the surface of the PCM container.

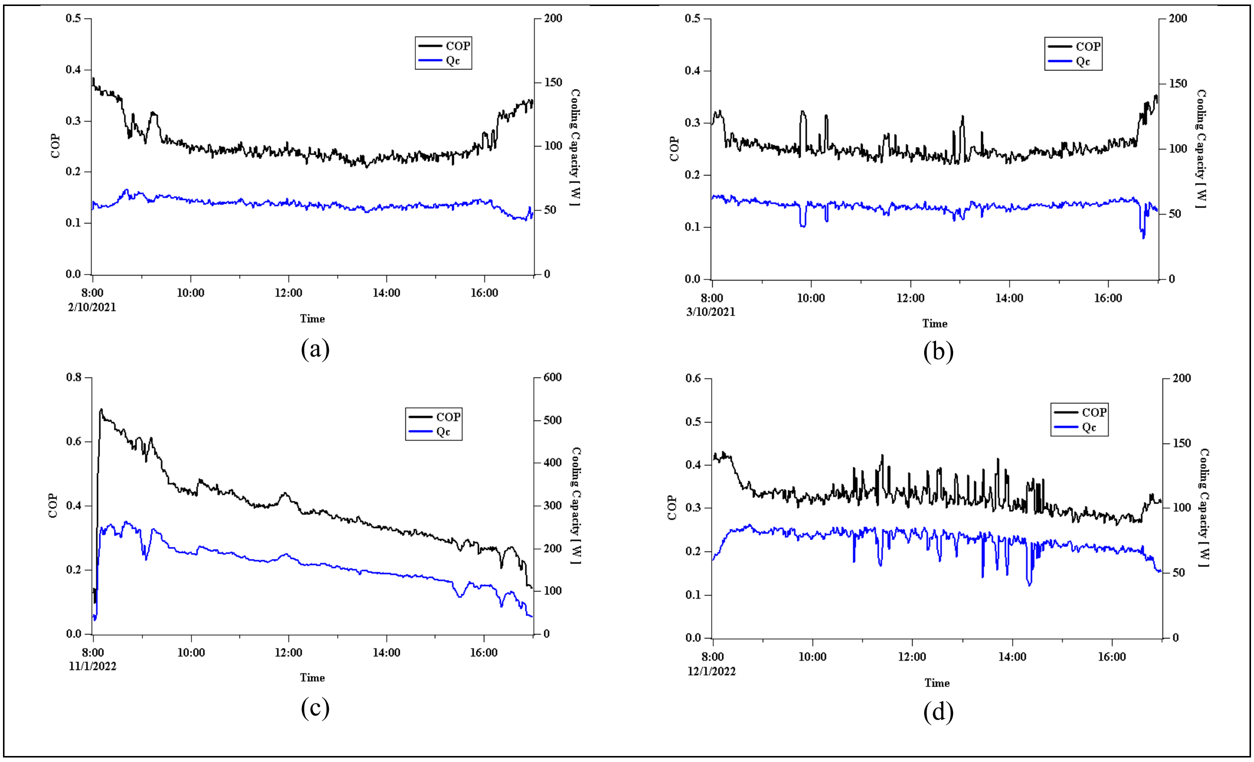



**Figure 7.** COP and cooling capacity of the cooling system during mode 2 experiment on (a) 1st day (2 October 2021), and (b) 2nd day (3 October 2021), and mode 3 experiment on (c) 1st day (11 January 2022), and (d) 2nd day (12 January 2022)

The variation of COP and cooling capacity during the mode 2 experiment in Fig. 7a and Fig. 7b shows that the maximum COP values of 0.38 and 0.35 on the 1st day and 2nd day of experiments, respectively, were achieved at the beginning or the end of the experiment. The higher COP values at the beginning and the end of the experiment were caused by the low electrical power supplied by the PV panels during those times and an insignificant decrease in cooling capacity. The average cooling COP for the entire experiment was 0.26 and 0.25 on the 1st and 2nd day of experiments, respectively. Cooling capacity showed the opposite trend to COP. The average cooling capacity achieved was 54.7 W and 56.4 W, respectively on the 1st day and 2nd day of experiments with a maximum cooling capacity of 67 W.

It can be seen in Fig. 7c that the COP of the cooling system on the first day of mode 3 experiment had an average value of 0.39 and the highest value of 0.7. Meanwhile, the cooling capacity had an average value of 160.4 W and the highest value is 264 W. The graph also shows that the COP of the cooling system was experiencing a downward trend due to the decreasing cooling capacity of the PCM. In Fig. 7d, it can be seen that the COP of the cooling system on the second day of mode 3 experiment had an average value of 0.32 and the highest value of 0.43. While the cooling capacity had an average value of 75 W and the highest value is 87.6 W. Variations in COP and cooling capacity on the second day of mode 3 experiment were more stable because the PCM temperature was starting to approach room temperature.

## 4. Conclusion

This study evaluated the performance of a cooling system and its influence on room temperature and relative humidity in a test room through three experimental modes. Mode 1 was used as the reference condition without a cooling system, Mode 2 applied a thermoelectric cooling system, and Mode 3 used a thermoelectric cooling system combined with phase change materials. The comparison among these three modes shows that the addition of PCM in the solar cold energy storage system contributed to better cooling performance in the test room. Based on the visualization of air temperature distribution using data from 27 temperature sensor points, Mode 3 produced the most uniform temperature distribution compared with the other experimental modes. The temperature difference between the upper and lower parts of the test room in Mode 3 was only 0.6°C, indicating that the combination of thermoelectric cooling and PCM helped reduce temperature variation within the room. The experiment also showed that the lowest relative humidity was achieved in Mode 3. On the first day of the Mode 3 experiment, the relative humidity decreased from 70% at 08:00 AM to 58% at 01:30 PM. This result indicates that the use of PCM in the cooling system not only supported temperature reduction but also contributed to lowering the humidity level inside the test room. The addition of PCM also improved the coefficient of performance of the cooling unit. In Mode 3, the average COP increased by 50% on the first day and by 27.5% on the second day compared with the thermoelectric cooling system without PCM. However, the performance improvement decreased on the second day because the PCM temperature gradually approached room temperature, reducing its ability to absorb heat effectively. Overall, the results indicate that solar cold energy storage using thermoelectric cooling and PCM has potential as an alternative cooling strategy for small-scale room applications, although further optimization is required to improve long-term performance stability.

## 5. Acknowledgments

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## 6. Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. The research was conducted objectively, and no personal, financial, or institutional interests influenced the experimental process, data analysis, interpretation, or conclusions of the study.

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