Performance Analysis of a Solar Dryer Equipped with a Phase Change Material Thermal Storage Unit

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Abstract

There are various ways of storing thermal energy to improve the efficiency of solar dryers. In this application, paraffin wax as a phase change material (PCM) was used as the thermal energy storage medium. It was used because of its advantages over other PCMs, which include high latent heat of fusion, non-flammability, and most importantly, because it is readily available and cheap. The thermal energy storage was then coupled with the solar dryer used to dry banana slices. The drying rate of banana slices increased from 54% without thermal energy storage to 69% with the thermal energy storage incorporated. The thermal energy storage stores about 3,513 KJ of thermal energy. By incorporating the thermal energy storage with the solar dryer, the drying rate is increased, and the spoilage rate of the food item is decreased because there is continuous drying as the thermal energy storage provides the thermal energy needed for drying.

Keywords: Phase change material, solar dryer, banana slices, drying rate, thermal storage

1. Introduction

Thermal energy storage (TES) is one of the key technologies for energy conservation and, therefore, is of great practical importance as it is used for thermal applications such as space and water heating, cooling, air-conditioning, etc. (Dincer & Rosen, 2001). Thermal energy storage (TES) systems can simply be defined as systems that can store heat or cold to be used later, under varying conditions such as temperature, place, or power (source). Thermal energy storage systems are very cost-effective compared to other storage technologies. In terms of environmental impact, it is a clean energy storage technology (Ahmet & Yağmur, 2021). TES systems are divided into three types: sensible heat, latent heat, and thermochemical. Phase change materials (PCM) are examples of latent heat storage materials (Cabeza, Martorell, & Barreneche, 2015). PCMs provide higher energy storage density, since latent heat values are significantly higher than sensible heat.

Paraffin wax is one of the phase change materials that absorbs heat energy and releases it later when in demand. Paraffin wax is a by-product of heating or distilling petroleum, also known as crude oil (Rao & Zhang, 2011). The daily and seasonal fluctuations in the irradiation level require using energy accumulators with phase change materials to achieve sustained drying processes. The successful usage of PCMs is, on one hand, a question of high energy storage density, but on the other hand, it is very important to be able to charge and discharge the energy storage with a thermal power that is suitable for the desired application. Paraffin wax is selected for this application because it is locally available and cheap, compared to other phase change materials. Additionally, it has a high latent heat of fusion, high specific heat, is non-flammable, and has a high density.

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Table 1 shows thermo-physical properties of paraffin wax and aluminum wool (Bugaje, 1997)

Table 1: Thermo-physical properties of paraffin wax

Property	Value
Latent heat of fusion	214kJ/kg
Specific heat capacity(solid)	1.85kJ/kg K
Specific heat capacity (liquid)	2.384kJ/kg K
Thermal conductivity	0.4W/mk
Density(solid)	856kg/m³
Density(liquid)	775kg/m³
Melting point	60˚ C

Solar dryers, which harness solar energy for dehydrating substances, particularly food, are generally classified into two types: direct and indirect. Direct solar dryers expose the substance directly to sunlight by placing it on a black absorbing surface that collects light and converts it to heat, often incorporating enclosures, glass covers, or vents to improve efficiency. A persistent challenge in solar drying and various industrial processes is the mismatch between the period of thermal energy availability and the period of actual usage, creating a need for effective storage methods that capture excess heat for later applications. Latent heat thermal energy storage (LHTES) offers one of the most efficient solutions to this disparity, enabling stored energy to correct the gap between production and consumption while minimizing waste and improving overall process efficiency (Tiari, 2015). Compared to sensible heat thermal energy storage (SHTES) systems, LHTES systems provide the advantage of storing significantly higher amounts of energy per unit mass of storage material. However, a notable limitation persists, most commercially viable phase change materials (PCMs) used in LHTES systems suffer from inherently low thermal conductivity, which constrains their performance.

The intermittent nature of solar energy, driven by daily and seasonal fluctuations, necessitates the integration of thermal energy accumulators using Phase Change Materials (PCMs) to enable a continuous drying process, as these materials leverage the latent heat of phase change (typically solid-liquid) to achieve high energy storage density with minimal temperature variation, making them ideal for temperature stabilization and compact storage (Daulatrao, 2017). While the successful application of PCMs depends on their high volumetric melting enthalpy (combining high melting enthalpy [kJ/kg] and density [kg/m³]), a significant drawback is their inherently low thermal conductivity, which limits the thermal power that can be extracted during charging and discharging cycles. In a typical solar dryer configuration, during sunshine hours, a solar air flat plate collector (FPC) supplies heat directly to the dryer cabin while simultaneously charging the PCM unit; during off-sunshine hours, a three-way valve redirects airflow through the thermal storage unit, where air is heated by the latent heat released during PCM solidification before entering the dryer cabin, with a draft fan maintaining consistent airflow throughout the assembly (Daulatrao, 2017).

The limitations of relying on backup heaters without integrated thermal storage are evident in the direct solar-biomass dryer developed by Prasad and Vijay (2005) as in Figure 1. Their design incorporated a biomass burner with a rock slab to help moderate drying air temperatures, yet it lacked any means of storing captured solar energy. Consequently, the air temperature within the drying chamber would drop to ambient levels immediately after sunset, necessitating backup heating even following a perfectly sunny day—an inefficiency that results in wasted solar and fuel resources (Prasad & Vijay, 2005). This reliance on biomass is particularly significant given that fuel wood remains a dominant energy source across most developing countries, where it is commonly burned using inefficient technologies (Bena & Fuller, 2002). While biomass can provide sustainable backup for solar drying if harvested responsibly, there remains a notable gap in research regarding dryer designs that successfully integrate collector-storage solar systems with biomass-backup heaters.

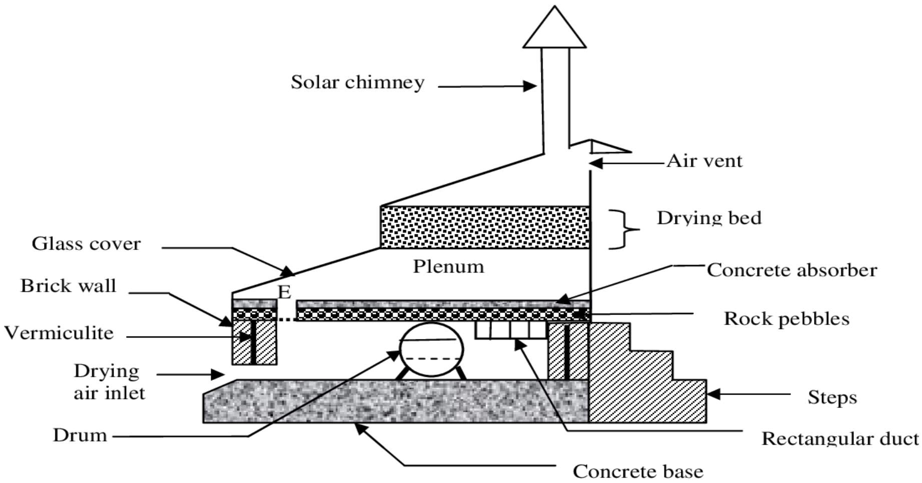

Figure 1: Solar dryer with thermal storage and biomass backup heater

Some solar dryers utilize sand as thermal energy storage medium. As a material, sand offers a compelling combination of durability, affordability, and high energy density, capable of storing substantial heat within a small volume at temperatures reaching 500–600 degrees Celsius—a single storage unit can deliver 100 kW of heating power with an 8 MWh energy capacity, representing a meaningful contribution to the smart and green energy transition (Purtill, 2022). The suitability of sand as a sensible heat storage material stem from its high specific heat, thermal stability, and low cost. In one proposed design, a simple air heater with an integrated thermal energy storage system was analysed, utilizing copper tubes as absorbers filled with two different storage materials: sand for sensible heat storage and paraffin wax for latent heat storage. The system successfully maintained outlet temperatures 5°C above ambient for approximately 16 hours. Performance comparisons revealed that at a mass flow rate of 0.02 kg/s, the daily average efficiency reached 59% with sand, while paraffin wax achieved a slightly higher 63.35%. Further investigation into the effect of air mass flow rate demonstrated that increasing the flow rate enhanced heat transfer but consequently reduced the effective discharge period.

Some other dryers utilize gravel as thermal energy storage medium. A study investigating the drying of chilli evaluated the performance of a solar dryer system incorporating a thermal energy storage (TES) unit using gravel as the heat storage material. The system (Figure 2) consisted of a solar air heater with integrated heat storage, a drying chamber, and a blower. The solar air heater featured a glass cover and a commercially black-painted copper absorber plate, with the gap between the absorber plate and insulation filled with sand particles mixed with aluminium scraps—a configuration designed to store thermal energy during peak sunshine hours and release it for heating air during off-peak periods. The drying chamber was designed to hold 50 kg of chilli per batch, and the solar air heater was positioned at a 25° inclination. Conducted at an air flow rate of 0.25 kg/s, the experiment successfully reduced the moisture content of chilli from an initial 72.8% (wet basis) to final moisture contents of approximately 9.2% and 9.7% (wet basis) within just 24 hours. The incorporation of the heat storage unit proved effective in enhancing system performance, extending the drying duration by 4 hours per day. The thermal efficiency of the system was recorded at approximately 21% (Mohanraj, 2009).

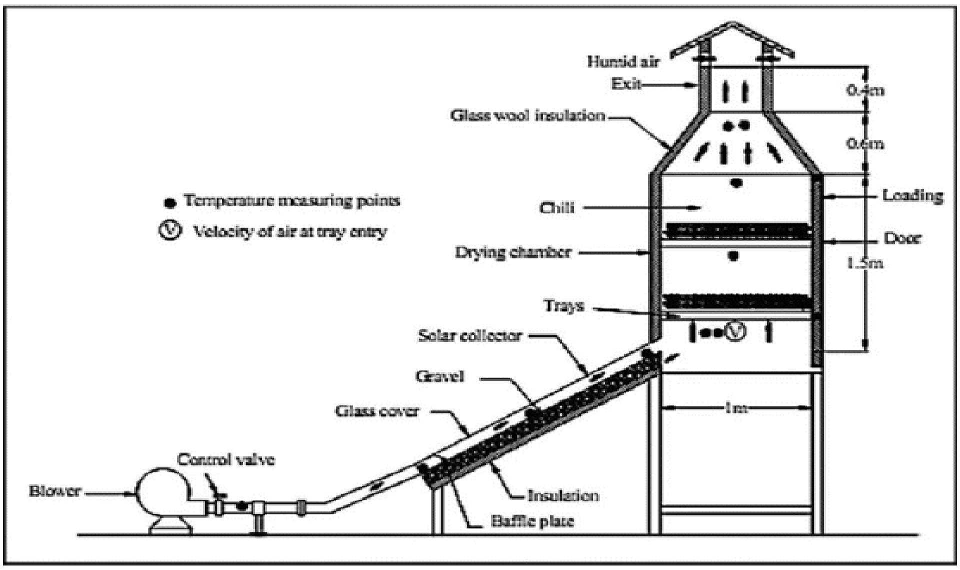

Figure 2: Gravel as a thermal energy storage in a setup

Some researchers have used an aggregate of concrete, sand and rock as thermal energy storage device. In a study, an experiment was conducted to improve the thermal performance of a natural convection solar greenhouse dryer using concrete, sand, and rock as sensible heat storage materials, with trials revealing that a 4-inch thickness layer was optimal for both sand and rock to enhance drying during day and night (Ayyappan, 2016). Using coconut as the drying product, the system achieved moisture reduction from 52% to 7% (wet basis) in varying durations depending on the storage material. Concrete required 78 hours, saving approximately 55% of drying time compared to open sun drying at 174 hours. Sand further reduced drying time to 66 hours, yielding a 62% time saving, while rock proved most effective at 53 hours with a 69% time saving. Thermal efficiency results showed rock performed best at 11.65%, followed by concrete and then sand at 9.5% (Ayyappan S, 2016). Following examination of various thermal storage approaches, phase change materials (PCMs) emerge as a compelling alternative to sensible storage materials like sand, as they store both sensible and latent heat rather than relying solely on sensible heat which dissipates quickly. PCMs fundamentally depend on latent heat storage, meaning they can store or release large amounts of energy at a nearly constant temperature during aggregate state changes, with minimal temperature difference required between charging and discharging cycles (Pasupathy & Seeniraj, 2008).

The current study, therefore, analysed the use of paraffin wax as a phase change material to support thermal storage in an existing solar dryer. The study investigated the application of paraffin wax as a phase change material in thermal storage for improving the drying rate of an existing solar dryer using banana slices for experimentation.

2. Methodology

This section presents systematic methods implemented to achieve the research objectives. A thermal energy storage system was developed and incorporated into an existing solar dryer (Figure 3). Since the main aim of this study is to harvest solar energy and store it for later use, the thermal energy storage was first tested for time taken to charge the storage during the day using a data harvester and the temperature was recorded at intervals of 30mins until there was no significant change in the temperature inside the storage. Thermal equilibrium was achieved at 50˚C.

Figure 3: Existing solar dryer

Drying using the existing solar dryer began in the morning, using only the solar dryer without it being connected to the developed thermal storage system (Figure 4). Instead, the thermal storage system was undergoing charging. The drying rate was tested for two scenarios: no thermal storage system connected and when the thermal storage system was connected during hours of no sunshine availability. For no thermal storage system connected, the mass of the samples of fresh banana slices was dried from 434.3 g to 201.1 g within 24 hours. For the test with the thermal storage system connected, the banana slices weighing 436.4g before drying, weighed 135.8 g after 24 hours.

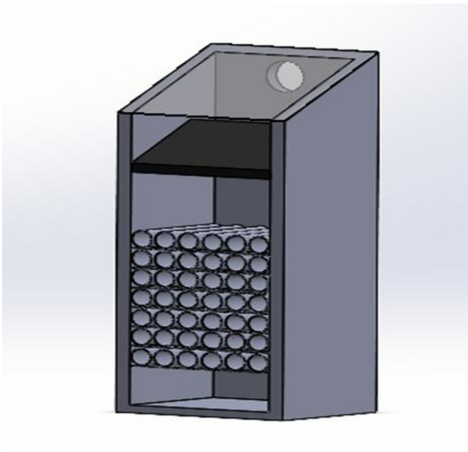

Figure 4: SolidWorks rendition of the designed thermal storage system

2.1 Material selection for the thermal storage unit

The storage unit casing is constructed using plywood as it can act as a very good insulator, thus less heat will be lost from the storage unit. Aluminum tubes were used to contain PCMs and were designed in a way that allows the PCM to be easily removed and refilled in the tubes. The thermal energy storage is equipped with a flat plate collector that is made of stainless-steel sheet to absorb radiation from the sun. The flat plate collector is painted black to increase the emissivity of the material and maximize heat absorption and heat dissipation into the storage unit.

Air, which is the heat transfer fluid, is blown into the storage unit by means of a blower that is incorporated at the inlet and this helped transfer heat from the flat plate collector to the PCM tubes during daytime (charging) and from the PCM tubes to the drying unit at night (discharging). Control valves are also used in the thermal energy storage unit to direct the flow of the heat transfer fluid either to the PCMs for charging or from the PCMs to the drying unit for the drying purpose. A support structure that is incorporated with the solar dryer was made so that the solar dryer and the thermal energy storage can be one component.

2.2 Design considerations of storage tank

2.2.1 Heat stored by the Phase Change Material

By increasing the temperature of the Phase Change Material, the PCM gains sensible energy from initial temperature (T_i) to its melting temperature (T_m). After being liquified, PCM now gains latent heat from constant temperature which is the useful energy for this study. The amount of heat stored by PCM was calculated as shown in Equation 1.

$$Q = m\left[C_{sp}(T_m - T_i) + a_m \Delta h_m + C_{lp}\left(T_f - T_m\right)\right] \qquad \text{(eq. 1)}$$

$$Q = 10[1.85(60 - 18) + 1(214) + 2.384(85 - 60)]$$

$$Q = 3513KJ$$

2.2.2 Required volume of phase change material

The amount of the Phase Change Material to be used was made to be of sufficient capacity to store the amount of thermal energy required. The required volume of the Phase Change Material to use was calculated as shown in Equation 2.

$$V_{pcm} = \frac{m_{pcm}}{\rho_{pcm}} \qquad \text{(eq. 2)}$$

$$V_{pcm} = \frac{10}{775}$$

$$V_{pcm} = 0.0129m^3$$

2.2.3 The length of the PCM tube (L_{pcmt})

The total length of the PCM tube to be used was calculated using Equation 3.

$$L_{pcmt} = \frac{4(V_{pcm})}{\pi n d_{it}^2} \qquad \text{(eq. 3)}$$

$$L_{pcmt} = \frac{4(0.0129)}{(\pi)(21)(0.04^2)}$$

$L_{pcmt} = 0.489$ m $\qquad L_{pcmt} \approx 0.5$ m

2.2.4 The volumetric flowrate of the heat transfer fluid

The volumetric flowrate of the HTF at the inlet was also calculated using Equation 4 and the velocity was assumed to be 1.5 m/s which is between 0.5 m/s and 5.08 m/s as recommended by (Scanlin, 1997). The inlet whole diameter was assumed to be 80mm which is equivalent to the height between flat plate collector and the glazing glass.

$$\dot{\upsilon} = u \times A_{inlet} \quad \text{(eq. 4)}$$

$$\dot{\upsilon} = 1.5 \times (\pi \times 0.04^2)$$

$$\dot{\upsilon} = 0.0075\ m^3/s$$

2.2.5 The mass flow rate of Heat Transfer Fluid

To ensure air was not restricted within the thermal energy storage, the inlet of the thermal storage unit was employed, and the mass flow rate was calculated using Equation 5 and was found to be

$$\dot{m} = \dot{\upsilon}(\rho_{HTF}) \quad \text{(eq. 5)}$$

$$\dot{m} = 0.0075(1.225)$$

$$\dot{m} = 0.0092\ kg/s$$

2.2.6 The Reynold's number for the Heat Transfer Fluid

The Reynold's number for the HTF was calculated using Equation 6 which specifies the flow pattern of a fluid.

$$R_e = \frac{2(\rho_{htf})(u)(r_{ii})}{\mu_{htf}} \quad \text{(eq. 6)}$$

$$R_e = \frac{2(1.225)(1.5)(0.04)}{1.81 \times 10^{-5}}$$

$$R_e = 8121.5$$

From the number Reynold's number obtained it can be concluded that the flow is turbulent since the number obtained is greater than 4000.

2.2.7 Performance Evaluation

The performance of the dryer with the thermal energy storage was evaluated in 2 ways. Firstly, bananas were used to test the system. The banana samples were sliced to prepare them for introduction into the drying chamber. The efficiency of the solar dryer was evaluated firstly without the thermal energy storage, where banana slices were dried with the thermal energy storage disconnected from the dryer for 24hrs. The thermal energy storage was then reconnected to the solar dryer to dry other fresh banana slices in 24hrs. Both dried banana samples were weighed to check if there is a significant difference in the moisture content removed from them. It is expected that banana slices dried with the thermal energy storage incorporated will have lost more moisture in 24hrs than those dried without the energy storage device.

3. Results and Analysis

Figure 5 presents the temperature profile of the paraffin wax PCM over a 24-hour period, illustrating the charging and discharging phases. During the charging phase (09:00 to 17:00), the PCM temperature increased steadily from ambient (22°C) to 65.8°C as it absorbed thermal energy from the solar collector. The rate of temperature increase was most pronounced between 09:00 and 12:00 (average heating rate of 8.5°C/hour), corresponding to peak solar radiation intensity. Between 12:00 and 15:00, the heating rate decreased as the PCM approached its melting point, with a noticeable plateau beginning around 58-60°C, indicating the onset of phase transition.

The total charging time of 8 hours was sufficient to completely melt the 10 kg of paraffin wax, storing approximately 3,513 kJ of thermal energy as calculated in Section 2.2.1. This energy storage capacity aligns with theoretical values in literature, confirming that the design calculations were accurate and that heat losses during charging were minimal due to effective insulation.

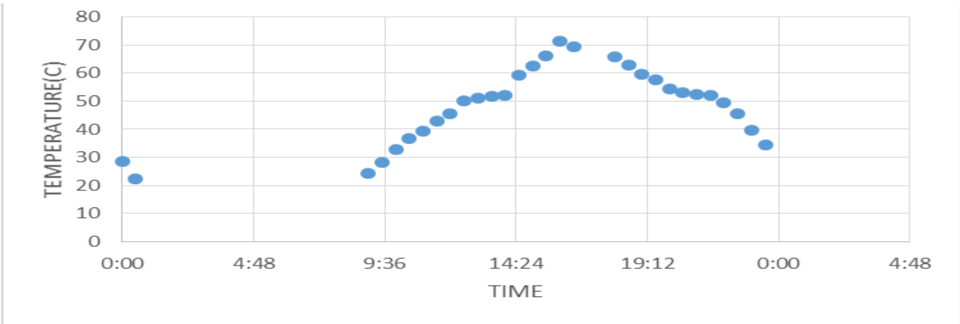

Figure 5: Temperature against time of day

The discharging phase (after 18:00) exhibited three distinct regions. Sensible heat release (18:00-19:00), temperature decreased from 72.8°C to 58.2°C as the liquid PCM released sensible heat. Latent heat release (19:00-22:00): Temperature remained relatively constant (55.7°C to 53.5°C) during solidification, with the plateau indicating the release of latent heat. This phase lasted approximately 3 hours and provided a stable heat source for drying. Final sensible heat release (after 22:00): Temperature decreased more rapidly from 53.5°C to 22.2°C as the solidified PCM released remaining sensible heat.

The effective discharging time (period during which the PCM maintained temperatures significantly above ambient) was approximately 6 hours, which is adequate for extending drying operations through the night in Botswana's climate.

Figure 6 compares the moisture content reduction of banana slices dried with and without the TES unit over a 24-hour period. For Scenario 1 (without TES), the initial mass of 434.3 g decreased to 201.1 g after 24 hours, representing a moisture loss of 233.2 g. This corresponds to a drying efficiency of 54%.

For Scenario 2 (with TES), the initial mass of 436.4 g decreased to 135.8 g after 24 hours, representing a moisture loss of 300.6 g and a drying efficiency of 69%. The improvement of 15 percent is directly attributable to the thermal energy stored in PCM, which enabled continuous drying during the night when solar radiation was unavailable.

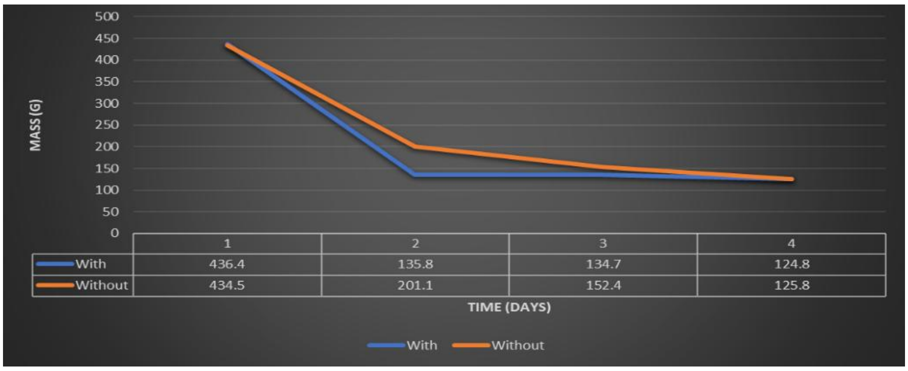

Figure 6: Moisture content with and without thermal energy storage

The drying rate curves in the figure below show that both scenarios exhibited similar behavior during the first 12 hours, with rapid moisture removal due to high solar radiation and elevated temperatures. However, after sunset (approximately 18:00), the drying rate for Scenario 1 decreased sharply as the system cooled to ambient temperature. In contrast, Scenario 2 maintained a higher drying rate until approximately 24:00, benefiting from the heat released by the PCM during its solidification phase.

4. Conclusion

This study successfully demonstrated the design, construction, and performance evaluation of a thermal energy storage unit using paraffin wax as a phase change material for an existing double-pass solar dryer. The paraffin wax-based TES unit, containing 10 kg of PCM in 21 aluminum tubes, achieved a theoretical storage capacity of 3,513 kJ and an actual effective discharging time of approximately 6 hours, sufficient to extend drying operations through the night. The incorporation of the TES unit improved the drying efficiency of banana slices from 54% (without storage) to 69% (with storage), representing a 15-percentage point increase in moisture removal over a 24-hour period.

The PCM exhibited distinct charging and discharging phases, with a stable temperature plateau during solidification that provided consistent heat delivery for drying applications. Turbulent flow conditions (Re = 8,121.5) achieved with the forced convection system enhanced heat transfer between the heat transfer fluid and PCM tubes, contributing to the system's overall performance.

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