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Research Paper

Comparison of Thermal Characteristics of Latent Heat Thermal Energy Storage (LHTES) Material of Various Configurations

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ABSTRACT: *Thermal Energy Storage (TES) plays a crucial role in optimizing energy efficiency, particularly in renewable energy applications, thereby contributing immensely to economic savings, energy conservation, preservation of fossil fuels and optimally sustainable environment. This experimental study comparatively investigates the thermal performance of paraffin wax as a phase change material (PCM) under three different configurations (aluminum mesh-with- PCM, aluminum foam-with- PCM and PCM -only). This is geared towards addressing the key energy challenges such as low thermal conductivity, unnecessarily prolonged charging/discharging period and material degradation often encountered by the current TES systems.*
A comparative assessment has been conducted for the three different configurations based on key performance parameters such as charging/discharging temperature profile, total energy storage/recovery capacity, charging/discharging duration and latent heat ratio. The experimental results indicate that the thermal response characteristics of each configuration were distinct. The insights gained from the highlighted potentials of the configurations in this current study, could inform improved development and applications of TES solutions particularly in regions with significant day-night temperature mismatch such as Ekiti State, Nigeria.

KEYWORDS: *Latent heat thermal energy storage, Configurations, Phase change material, Paraffin wax, Aluminium mesh, Aluminium foam, Melting*

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I. INTRODUCTION

There are considerable fluctuations between day and night temperatures in regions such as Ekiti State, Nigeria. While the daytime temperature tends to be high, there is usually relatively low temperature at nighttime and sporadically early morning. Maintaining a sustainable indoor thermal comfort both in homes and buildings in this region during those periods is always a serious problem, especially in the rural communities of Ekiti State where there is erratic electricity supply and hardly any energy-efficient heating or cooling systems. Therefore, it is not only uneconomical but usually not sustainable to employ energy-intensive heaters or air conditioners in those regions.

Thermal energy storage (TES) technology is one potential solution to this problem of the mismatch between the instantaneous energy demand and supply. TES works by storing excess heat during the warm period and releasing it during the cold period. TES plays an important role in the management of thermal energy and also in the implementation of peak and off-peak load shifting techniques for efficient use of resources like that in Ekiti State. Hence, maintaining indoor comfort without continuous energy use or much reliance on the national grid or the limited fossil fuels.

Thermal energy storage (TES) is one of the significant technologies for reducing the discrepancy between ever-increasing energy demand and utilization [1]. Basically, the three primary sorts of TES technology as shown in Figure 1 are: sensible heat thermal energy storage (SHTES), latent heat thermal energy storage

(LHTES), and thermochemical storage (TCS). While SHTES stores heat by raising the temperature of a material, such as water, rocks, molten salts etc., LHTES uses materials that absorb or release heat when they change their phases, such as from solid to liquid, from liquid to gas, etc. These materials remain at a nearly constant temperature during this phase change process, making them highly efficient. TCS on the other hand, works on the basis of storing energy in the form of chemical changes.

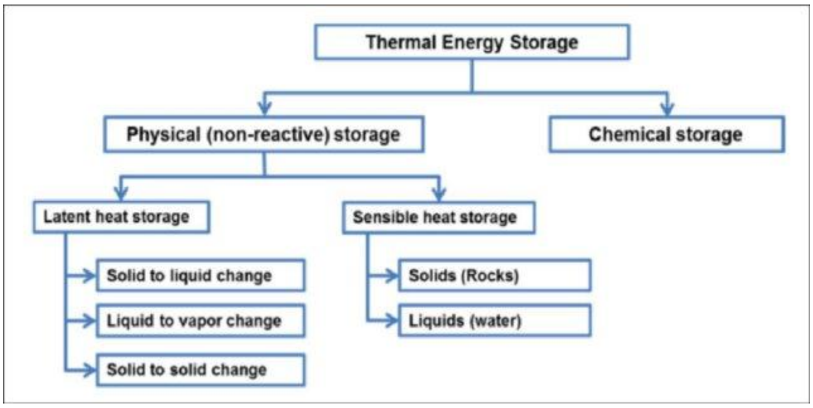

Figure 1: Thermal energy storage methods [2]

Among all these, LHTES possesses several advantageous characteristics over the others namely high energy storage density, chemical stability, substantial latent heat capacity, and the capability to sustain a nearly constant temperature [3, 4]. LHTES utilizes the Phase Change Materials (PCMs) to accommodate excess or intermittent thermal energy sources for a steady and controlled output, by storing and releasing the thermal energy within phase transformation process, making it a good fit for the temperature management services [5, 6]. The stored thermal energy can be used in a building in various aspects such as supplying warm water, underfloor space heating, or indirect heating with a heat pump system [7].

PCMs are widely recognized as the most effective method for storing cold energy or for heat recovery [8]. PCMs refer to substances that possess the ability to store and release significant quantities of energy during state transitions. This unique property renders them suitable for a wide range of applications, including energy storage and the regulation of thermal comfort [9].

PCMs have been beneficially utilized in various domains, including building energy preservation, solar energy harnessing, recuperation of waste heat, and other systems for storing thermal energy [10]. The integration of PCMs insulation in buildings contributes to the reduction of energy consumption and subsequent emissions. This is achieved by the ability of PCMs insulation to store surplus thermal energy which is subsequently released when required [11]. There are various types of PCMs which can be identified as PCMs from the point of melting temperature and latent heat of fusion [12]. These include organic PCMs like Paraffin wax, Fatty acids; inorganic PCMs like Salt hydrates, metal alloys; and eutectic PCMs which combine two or more organic or inorganic PCMs. Among all these, paraffin waxes are some of the most usable PCMs due to their stable phase change temperature, predictable performance, non-toxicity, availability, chemical inertness, low cost, high latent heat capacity, and ease of handling.

A proper TES system should be designed in such a way to possess a high heat transfer rate, energy efficiency, and exergy efficiency during the charging and discharging processes [7]. However, due to the issue of low thermal conductivity often encountered by LHTES systems, their effectiveness largely depends on how well PCMs are integrated into various configurations to optimize heat transfer and storage.

Extensive research studies have been previously conducted in a quest to mitigate this issue of low thermal conductivity of LHTES systems and thereby improving the thermal performance. These past efforts involved the incorporation of nanoparticles into the PCMs [13-17]; integration of metallic foam [18, 19]; encapsulation of the PCMs [20-23] and inclusion of expanded graphite [24-26]. In addition, in an attempt to achieve satisfactory melting and optimum solidification performance, other researchers like [1, 6, 23, 27] have focused attention on the utilization of various configurations in the design integration of PCM-based TES systems. However, while there have been several studies conducted on PCMs, just a few or none of them relate to climates that accurately represent the unique temperature profiles and also address the energy limitations at a rural Nigerian setting such as Ekiti State. Research efforts to date often do not compare configurations under conditions similar to those found in the Nigerian regions (such as Ekiti State) where day-night temperature swings are more pronounced. In addition, there is also a general lack of practical and localized research specifically addressing the optimization of TES systems in this region.

The present study addresses this gap and provides specific insight into how different configurations, including aluminum foam and aluminum mesh affect the thermal characteristics of Paraffin wax as a PCM under conditions representative of the operating challenges faced by residents in Ekiti State. This research is relevant for the better development of efficient and sustainable TES systems in striving to reduce energy use in buildings without compromising comfort. This study is aimed to contribute to the ongoing efforts toward alleviating energy insecurity and the dependency on fossil fuels for space heating and cooling in Nigerian households.

II. EXPERIMENTAL PROCEDURE

2.1 Preparation of Configurations

The experimental method was systematically carried out to examine the thermal behaviours of paraffin wax as PCM in three different configurations which are aluminium foam, aluminium mesh, and PCM only as shown in Figure 1. For consistency and reliability, each configuration was subjected to the same environmental and experimental conditions. The methodology focused on heating (charging) and cooling (discharging) phases in these configurations. In this study, samples of aluminium foam and aluminium mesh each of 25 x 15 mm^2 dimension were prepared such that they completely fit into the test tubes.

5 grams of grinded PCM (paraffin wax) was added to each of the test tubes containing the aluminium foam and aluminium mesh. The configurations were fully soaked in the wax to ensure appropriate thermal interaction. Again, 5 grams of paraffin wax was poured directly into a clean test tube directly into a clean test tube. The three test tubes were thoroughly insulated with cotton wool to prevent heat or mass interaction with the laboratory environment both during the heating (charging) and the cooling (discharging) phases.

Figure 2 Configuration materials before the experiment

2.2 Initial Setup

A water bath was filled with enough water to submerge the test tubes up to the level of the PCM to be tested, ensuring adequate uniform heat transfer. To monitor temperature changes, mercury-in-glass thermometer was inserted into each test tube, allowing for precise readings at regular intervals (every 30 seconds). The essence of the water bath provision is for the sustenance of desired temperatures during the heating and cooling phases with the aid of a temperature control system. Before starting the experiment, the insulation was confirmed to be secure and effective in all test tubes in order to maintain equal thermal conditions across all samples.

2.3 Heating Phase

The heating process began by placing the water bath, along with the test tubes containing the samples, on a heat source as shown in Figure 2. This arrangement enabled the water and the samples to be heated simultaneously, allowing for a gradual and uniform temperature increase. The temperature was carefully raised above the melting point of paraffin wax (55°C) but kept below 80°C to prevent evaporation or uncontrolled heating. The test tubes, containing the three different PCM configurations (aluminum foam-with-PCM, aluminum mesh-with-PCM and PCM-only), were fully submerged in the hot water, ensuring direct heat transfer from the surrounding liquid. Temperature variations and the stages of the phase change during the heating process were monitored and recorded to predict the thermal characteristics of each configuration. The heating process continued until the

PCM samples had completely melted (100% melting or molten mass ratio of 1), as confirmed by visual observation (a fully liquefied phase) and stable temperature readings.

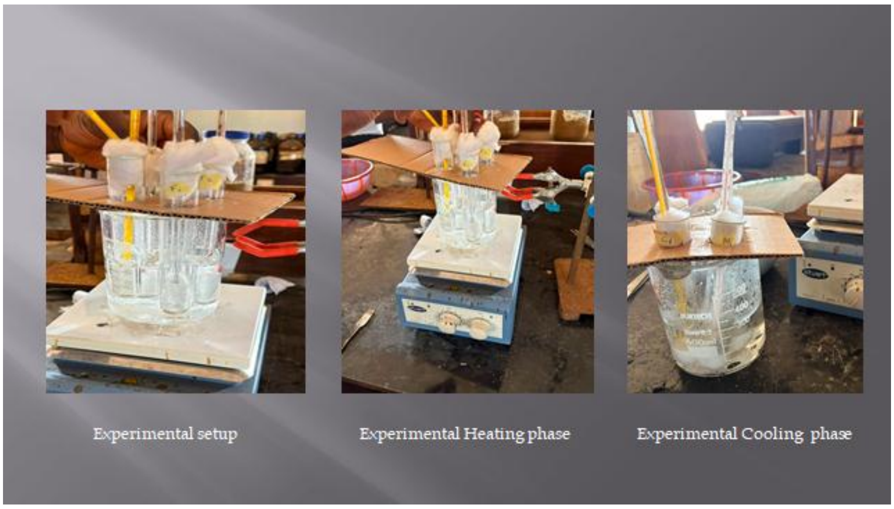

Figure 3: Photograph of the experimental set-up

2.4 Cooling Phase

The cooling phase began once the paraffin wax was fully melted as confirmed by observing a clear liquid phase and stable temperature readings less than 80°C. At this point, the heating source was turned off, and the water bath separated from the heating source as shown in Figure 2 was left to cool naturally without any external heating/cooling medium. This method was chosen to simulate real-world thermal energy storage (TES) discharge conditions. To ensure all samples experienced the same cooling conditions, no active cooling methods such as fans or ice were used. Instead, the water bath was allowed to cool down naturally. This helped to maintain a steady and uniform heat loss across all the PCM configurations allowing for a fair comparison of their cooling behaviours. As in the heating phase, temperature readings were taken every 30 seconds using mercury-in-glass thermometers, which were inserted directly into the PCM inside the test tubes. The insulation installation ensured that most of the heat escaped gradually through the test tube walls rather than from the top, reducing any inconsistencies caused by air movement. Thus, allowing the PCM to cool under controlled and uniform conditions. These experimental conditions were incorporated to observe, predict and compare the thermal behavior of the aluminum foam, aluminum mesh, and PCM only configurations more accurately. The cooling process continued until the samples temperatures dropped to around 30°C, marking complete solidification.

It is noteworthy that the whole experimental procedure (heating-cooling cycle) was repeated twice to ensure accuracy, consistency and repeatability in data collection and analysis. This detailed procedure provided a robust framework for reliably comparing the thermal characteristics of the three configurations: aluminum foam, aluminum mesh, and paraffin wax only. By maintaining consistent conditions and carefully preparing the samples, the experiment was designed to yield reliable results. The data collected from these phases provided valuable insights into how each configuration retains and releases heat, which is crucial for improving TES applications.

III. THEORETICAL ANALYSIS

The amount of total thermal energy either accumulated or recovered from the storage media during either charging or discharging respectively depends on the type of configuration involved. This was estimated for each configuration by equation 1 as:

$$Q_{T,conf} = Q_{S,conf} + Q_{L,conf} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

where the first term on the LHS of equation 1 represents the sensible portion of the total thermal energy while the RHS term is the latent portion for each configuration (Aluminium mesh-with-PCM, Aluminium foam-with-PCM, PCM-only).

$$Q_{S,conf} = m_{pcm} c_{p,conf} \Delta T_{conf} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .2$$

$$Q_{L,conf} = m_{pcm}H_{conf} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots 3$$

The latent heat ratio (LHR) of each configuration is expressed as:

$$LHR = \frac{Q_{L,conf}}{Q_{T,conf}} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots .4$$

The molten mass ratio (MMR) in each configuration is expressed as:

$$MMR = \frac{m_{l,conf}}{m_{pcm}} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots .5$$

The thermal characteristics of materials were taken from [1, 28-30] and presented in Table 1.

Table 1 Thermal properties of storage materials

Properties	**Units**	**Aluminium mesh**	**Aluminium foam**	**Paraffin wax**
Specific latent heat of fusion	kJ/kg	399	389	120.7
Specific heat capacity	kJ/kg K	0.9002	0.963	2.1
Phase change temperature range	℃	30-73	30-70	30-62

IV. RESULTS AND DISCUSSIONS

The results obtained through the experimental study of the thermal performance of the TES for the different configurations (aluminium foam-with-PCM, aluminium mesh-with-PCM, and PCM -only) considered were presented and analysed in this section. The key performance parameters such as the heating (charging) and the cooling (discharging) characteristics, charge and discharge time, latent heat ratio and total energy storage/recovery capacity of each storage configuration are evaluated and analysed. This performance analysis, which is crucial for improving TES applications, provides valuable insights into how each configuration retains and releases heat during the heating/charging and cooling/discharging processes respectively.

4.1 Variation of temperature during charging/discharging phase

In order to analyse the thermal characteristics of a LHTES system, the roles of both the charging and the discharging times are highly pertinent in determining the overall system functionality. The variation of temperature with time during the charging phase for the three configurations is presented in figure 3. As shown in figure 3, it should be noted that: the resulted experimental data proved that the thermal response time of every configuration was distinct and temperature increase is parabolic in general for all the configurations considered in this work. Precisely, aluminium mesh-with-PCM configuration reached the highest attainable temperature (100% molten ratio) of 73 ℃ within the shortest time averaging about 15.5 minutes. This was followed by the aluminium foam-with-PCM configuration which reached a temperature of 70 ℃ at 18 minutes. Conversely, it took the PCM -only configuration the longest time of 23 minutes to reach the lowest temperature of 62 ℃.

In comparing the temperature-time variations of the three configurations, it can be observed from figure 3 that, the rate of temperature increase for the PCM-only configuration is much higher in the early period of the charging phase than for both aluminium mesh-with- PCM configuration and aluminium foam-with- PCM configuration. This behavioural trend could be traceable to the dominance of internal energy gain of the aluminum in both aluminium mesh-with- PCM configuration and aluminium foam-with- PCM configuration over the internal energy gained by the PCM in them. However, as the charging phase advances, the PCM-only configuration temperature increase rate becomes much more gradual than those of the other two configurations. This is possibly due to the temperature increase in the high thermal conductivity-aluminum present in the aluminium mesh-with- PCM configuration and aluminium foam-with- PCM configuration.

In addition, the difference in the structural and geometrical configurations between aluminium mesh and aluminium foam could be responsible for the higher temperature attained by the aluminium mesh than the aluminium foam. This, points to the importance of geometrical and structural conductive enhancements. Therefore, the structured pattern of aluminum mesh configuration improves temperature increase and hence, improved rate of heat absorption when compared with the unstructured aluminum foam configuration.

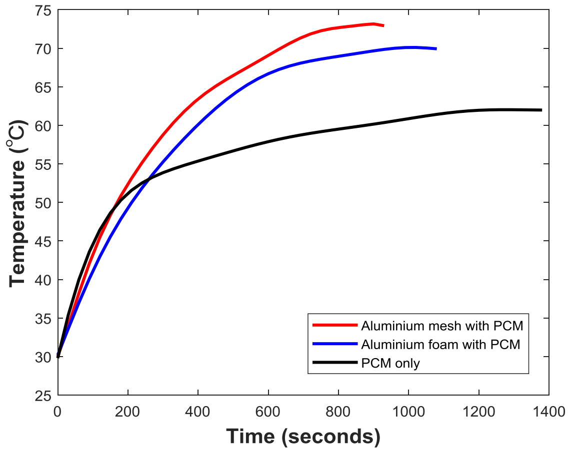

Figure 4 Variation of temperature with time during charging

As previously stated, the role of discharging time in determining the overall performance of a TES system is as important as the charging time. Figure 4 shows the variation of temperature with time during the discharging phase of the three configurations. Precisely, aluminium mesh-with- PCM configuration reached the lowest solidification temperature of 30 ℃ within the shortest time averaging about 35 minutes. This was followed by the aluminium foam-with- PCM configuration at 18 minutes. Contrastingly, it took the longest time of about 52.5 minutes for the PCM -only configuration.

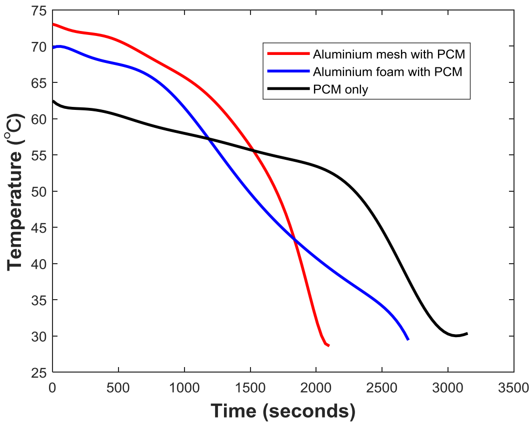

Figure 5 Variation of temperature with time during discharging

4.2 Total melting/solidification time for different configurations

Figure 5 shows the total melting/solidification time for the different configurations considered in this present study. As shown in figure 5, the PCM -only configuration has the longest melting/solidification duration followed by the aluminium foam-with- PCM configuration and the aluminium mesh-with- PCM configuration. The shortest discharging time shows that the aluminium mesh would dissipate its stored heat most easily. That is, its stored energy can be most easily and quickly retrieved when needed. The mesh provides a defined pathway for heat transfer, allowing for a controlled analysis of thermal conductivity and heat storage efficiency.

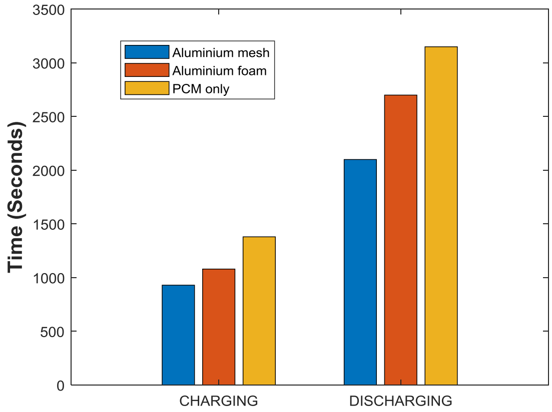

Figure 6 Total melting/solidification time for different configurations

4.3 Energy stored/released

The thermal energy storage capacity is one of the major factors for determining the overall performance of any TES system. The total energy stored/released of the different latent heat thermal energy storage configurations during charging/discharging phase respectively, is shown in figure 6. It is observed that, the aluminium mesh-with-PCM configuration displays the highest heat energy storage capacity, followed by aluminum foam-with-PCM configuration and then the PCM-only configuration. The aluminium mesh-with-PCM configuration and the aluminium foam-with-PCM configuration respectively have 2.30 and 2.27 times more energy storage/release potential than the PCM-only configuration.

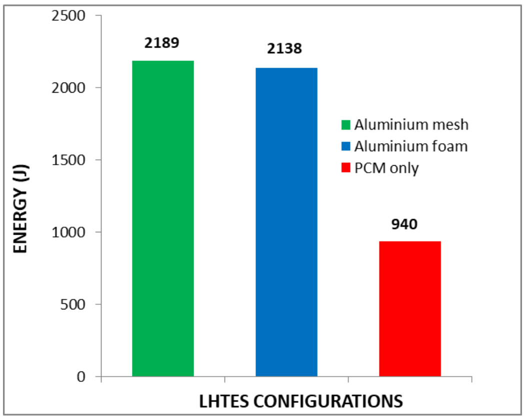

Figure 7 The Total energy variations of the different latent heat thermal energy storage configurations

4.4 Latent Heat Contribution

As shown in Table 2 regarding latent-sensible heat ratio, latent heat dominates the contribution in total energy stored/released as compared to sensible heat. Precisely, about 91.2%, 91% and 64.2 % of the total energy storage/released represents the latent heat contribution for aluminum mesh-with-PCM configuration, aluminum foam-with-PCM configuration and PCM-only configuration respectively. This shows that, in the TES system using paraffin wax, phase change process is indeed the dominant mechanism for energy storage/release.

Table 2 A summary of the thermal performance characteristics of the different storage configurations

Configuration	Maximum reached temperature ℃	Charging time (seconds)	Discharging time (seconds)	Total Energy (J)	Latent Heat Ratio (%)	Molten Mass Ratio (%)
Aluminium mesh with PCM	73	930	2100	2189	91.2	100
Aluminium foam with PCM	70	1080	2700	2138	91.0	100
PCM only	62	1380	3,150	940	64.2	100

V. CONCLUSION

In this study, an experimental investigation has been carried out to evaluate and compare the thermal performance of paraffin wax as a phase change material (PCM) under three different configurations (aluminum mesh-with-PCM, aluminum foam-with-PCM and PCM-only) to enhance heat transfer and storage capabilities. The overview of the obtained results from this current experimental research indicates that the aluminium mesh-with-PCM configuration has the:

- highest temperature rise, followed by the aluminum foam-with-PCM configuration and then the PCM-only configuration.
- shortest charging and discharging time, followed by the aluminum foam-with-PCM configuration and then the PCM-only configuration.
- highest heat storage capacity, followed by the aluminum foam-with-PCM configuration and then the PCM-only configuration.
- highest heat transfer rate, followed by the aluminum foam-with-PCM configuration and then the PCM-only configuration, and of course
- shortest melting time, followed by aluminum foam-with-PCM configuration and then the PCM-only configuration.
- In all the configurations, latent heat dominates the contribution in total energy stored/released, with about 64.2–91.2% as compared to sensible heat.

The data collected from these phases provided valuable insights into how each configuration retains and releases heat, which is crucial for improving TES applications. The present study results would be highly instrumental in the design, development and optimization of storage modules which have recently found a broad application in solar thermal power plants, thermal conditioning for buildings, sustainable transportation systems etc. This work may play a crucial role in both academics and practical energy applications, and would be one of the meaningful steps toward the understanding and optimization of PCM-based thermal energy storage in regions with significant day-night temperature mismatch such as Ekiti State, Nigeria.

Nomenclature

conf	Configuration
c_p	Specific heat capacity (kJ/kgK)
ΔT	Temperature difference (K)
H	Latent heat of fusion (kJ/kg)
LHR	Latent heat ratio
LHS	Left hand side
MMR	Molten mass ratio
m_{pcm}	mass of PCM in each configuration (kg)
$m_{l,conf}$	Molten mass in each configuration
Q_T	Total energy (kJ)
Q_S	Sensible heat
Q_L	Latent heat
RHS	Right hand side

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