A numerical investigation of a thermal storage water heating system using phase change materials

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Abstract. In this paper, the process of thermal heat storage within a water heating system utilizing phase change materials was numerically investigated using a CFD simulation. A two-dimensional model of the water-PCM energy storage system was designed and modelled using ANSYS Fluent. Two cases of without and with PCM were studied to investigate the possibility of using PCM materials in water storage heating systems. Paraffin wax with a melting temperature of 52 °C is used as the PCM material. Results showed that PCM (can maintain the water temperature at a higher level than that of without using PCM that meets the thermal requirements of water heating storage systems for domestic application. Also, results showed that the water temperature at the end of the simulation reaches 39.7 and 48.2 °C for the cases of without and with using PCM respectively. This means the final temperature of with PCM case is 8.5 °C higher than that of without PCM case and a temperature increase of about 21.46% can be achieved. This study highlighted the advantage of using PCM materials in water storage heating systems.

Keywords: Energy storage; PCM; paraffin wax

1. Introduction.
It has become clear over the ears that energy is one of the most important ingredients for any civilised society, and all sectors in modern society now require increasing amounts, causing a continuous increase in the global demand for energy. As 90% of global energy production is currently based on burning fossil fuels which not only cause pollution problems and global warming but also are due to run out very soon, a global search for alternative sources of energy has begun in an attempt to ensure the continuous abundance of energy. This has caused more attention to be paid the process of thermal storage of surplus energy and its subsequent use [1]. The exploitation of renewable energy sources such as solar energy or wind energy is one of the solutions to diversifying energy sources effectively, and the lack of constant availability of these sources due to various cyclic and variable properties has thus prompted research into energy storage, including thermal energy storage [2].

Thermal energy storage methods (TES) are divided into two categories:

- Sensible heat storage (SHS)
This is the process of storing thermal energy in the material, whether liquid or solid, such as water, rocks, and bricks, by raising its temperature to a certain level without causing its structural or physical condition
to be changed. The stored heat thus available is small as compared with that made possible by latent heat storage (LHS), so one of the most important disadvantages is the need for a large storage unit volume to store an amount of heat equal to a smaller latent thermal storage solution. Water is the best material for this type of storage due to its high specific heat, as well as this being both inexpensive and generally available; however, it can only be used within the low-temperature range due to the high pressure of its vapor. Water can also be used as a medium for the transfer of heat energy, especially in solar energy applications between 25 to 90 °C[3][4].

- Latent heat storage (LHS).

This is the process of storing heat in a material during its transformation from one phase to another based on establishing the temperature of the material; transformation types may be solid-solid, solid-liquid, solid-gas, liquid-gas, or vice versa. Materials that display these types of transformation are called phase-change materials (PCMs), and they are generally arranged into the three categories: organic, inorganic and eutectic. The selection of a PCM depends on many considerations, including thermal, physical, chemical, and economic factors, though the two most important considerations are generally the range of application temperatures required and the latent temperature of the material. The temperature of hot water applications for heating purposes is usually between 50 to 60 °C, while hot water for domestic use is about 40 to 50 °C [5]. Natural paraffin with the chemical formula CnH2n + 2 is a pure alkane, and it is the most widely used PCM, due to multiple positive features, which include sufficiently high latent heat capacity, limited size changes during phase change, chemical stability, low cost, and market availability. However, its largest drawbacks are its low thermal conductivity, which means that it needs to transfer heat to a large area, and its melting temperature, which ranges from 20 to 70 °C [6][7].

Many researchers have experimentally and theoretically studied the effects of phase-changing materials and their thermophysical properties in multiple industrial, domestic, and commercial settings. Olubunmi and Ajayi [2] examined the effect of using commercial wax with a melting point of 45 °C on solar water heating systems, using experimental tests to show that a higher maximum daily water temperature can be achieved with PCM as compared to those achieved in its absence. Mongibello et al. [8] performed an experimental study in the laboratory using a device designed to heat water that was reinforced with paraffin wax with a melting temperature of 58 °C as a PCM. A series of tests were performed at different flow rates on models with and without the PCM, and the results confirmed both the relevance of using PCM in thermal storage and the weak thermal conductivity of PCM, thus highlighting the need to use materials with higher conductivity to enhance thermal conductivity.

Senthil and Cheralathan [9] experimentally studied a water heating system for cooking or electricity generation with results that indicated that the efficiency of the system was increased by the presence of PCM material by 5.6% and that the time required for boiling water thus decreased by 20%; increases in the rate of water flow were found to lead to increases in the efficiency of the system. Nasir et al. [10] experimentally examined a solar water heater system, with results that showed that the time required to melt all the included wax was just 3 to 4 hours in the summer, while 14 to 16 hours were required in the winter. The ratio between the intensity of the solar radiation and the stored energy was direct, while the ratio between the water flow rate and the melting time was inverse. Pakalka, et al. [7] experimentally studied the main factors affecting the performance of the PCM storage system, including the architecture of the PCM container. They concluded that the heat transfer area could be increased by inserting a group of fins into the PCM material to improve thermal conductivity and reduce melting time. Similarly, Chaichan et al. [11] used experimental tests to examine the use of pebbles as sensible heat storage material, with paraffin wax used for latent heat storage, in a solar water heater for domestic applications. The results showed that the use of these materials affected the system's efficiency in terms of storing heat better and increasing storage hours, but that PCM materials were more efficient than pebbles. Reddy et al.
[12] experimented with different shapes and sizes of packages (spherical, cylindrical, and square capsules) made of stainless steel packed with PCM materials. The results showed that the cylindrical shape was the most effective for the process of charging and discharging heat.

Kenfack and Bauer [13] used an experimental investigation to develop a new phase-change material to overcome the phase separation phenomenon by adding other materials such as aluminum sulfate hydrate, $\text{Al}_2(\text{SO}_4)\cdot 3.18\text{H}_2\text{O}$, to a salt hydrate and studying the resulting behaviours. Multiple PCM materials, such as water, oil, pure salt hydrate, and the newly developed salt hydrate were used. Graphite was also added to the developed salt hydrate PYCO-PCM-1 to improve thermal conductivity. The results indicated that the new material, PYCO-PCM-1, demonstrates stable thermal behaviours and a high storage capacity as compared to the other materials tested, while the addition of 5% graphite to PYCO-PCM-1 has improved thermal conductivity by as much as 40%.

Kadim et al. [14] experimentally tested the behaviours of a PCM during the fusion and solidification process, as well as the effect of adding copper brushes, at different void fractions (97%, 94%, 90%) in terms of the thermal conductivity of paraffin wax. The results indicated that increases in the airflow rate increase the amount of heat transferred and reduce the hardening time, especially in the presence of a copper brush. The lowest melting time occurred at 90% void fraction with the highest air flow velocity, and this was 4.46 times faster than in the absence of a copper brush. Abdulmunem [15] performed an experimental study on passively cooling PV panels and regulating their temperature using a variable phase PCM. An aluminium matrix was added to improve the physical properties of paraffin wax, especially the thermal conductivity, and the process resulted in a decrease in the temperature of the photovoltaic panel from 61.39 °C to 46.2 °C for the PCM only, and a decrease to 39.58 °C when using the matrix of aluminium foam with the PCM material, which improved the efficiency of the photovoltaic work from 10.19% to 12.73%. Mahmud et al. [16] used MATLAB to calculate the thermal-physical properties of paraffin to which 5% aluminium powder was added to overcome the low thermal conductivity of PCM. It was observed that, during the process of energy discharge, for faster flows of air and lower temperatures of outgoing air, the setting time of PCM decreased, taking 8 hours at a flow rate of 0.05 kg/s, and about 3.5 hours at a flow rate of 0.19 kg/s.

Solano et al. [17] performed a digital analysis of a closed-type solar water heating system, with results that showed that the storage of thermal energy increased by about 2.2 times in summer as compared to winter and that the addition of fins led to reduced melting times and increased storage of thermal energy. Shareef et al. [18] then undertook an experimental study on the advantages of using a PCM in a solar water heating system to compensate for the absence of solar energy during the night, with 8 kg of paraffin wax dissolved at 52 °C forming 30% of the water volume of an iron tank. That study concluded that the hot water produced by using PCM materials was about 7.5 °C higher than for water alone.

The current study aimed to design a two-dimensional numerical model simulation utilising computational fluid dynamics (CFD) to verify the thermal behaviours of paraffin wax material as used as a PCM, and the effects of such use, with regard to latent heat storage and sensible heat, on the efficiency of heat storage in a water tank.
2. Numerical investigation

2.1. Numerical modeler

A two-dimensional physical model was used to simulate the water heating system examined in this study. In the first case (without PCM), a model consisting of five bodies, a container for water, water, air, a heater, and a glass wall insulating the tank was used, while in the second case, 10 bottles of aluminium were filled with PCM and divided into two rows, each row containing 5 bottles. The volume ratio of PCM to water to be heated was 31%. The geometry of the PCM container was determined using the Space claim program to ensure the required accuracy. Figure 1 shows a schematic diagram of the proposed model, while Table 1 shows the specifications and measurements for each component of the model.

![Figure 1. 2-D model of water tank (a) without PCM, (b) with PCM container.](image)

| Component          | Diminutions (mm) | Material   |
|--------------------|------------------|------------|
| Water tank         | L=750, w =285, t =2 | steel      |
| Water domain       | L=500, w =285    | water      |
| Air domain         | L=250, w =285    | air        |
| PCM container      | h=130, D=50      | aluminium  |
| Heater element     | D =50            | copper     |

In the mesh generation stage, a quadrilateral unstructured mesh element was used to obtain a stable convergence solution [19]. It is possible to control the mesh size that makes up the elements of such a
model, and, in general, the smaller the mesh size, the greater the number of mesh elements and greater the accuracy of the solution. The simulation geometry model was thus tested for the case in which the PCM material was used to determine the most appropriate mesh size for the simulation process; this was then generalised to the first case (without PCM).

The test mesh showed that the utilising large mesh created a difference in results of more than 3% compared to the results for the optimal mesh size.

![Figure 2. Mesh dependency test: number of elements and liquid fraction.](image)

Using the inflection option, the number of layers around the same element was increased from 8 to 10 to develop accuracy and reduce error. Several numerical tests were carried out to determine the most accurate solution. Table 2 and Figure 3 show the mesh size and the mesh used for Case 1 (without PCM).

### Table 2: Mesh generation for Case 1 (without PCM).

| Component name   | Element mesh size, mm | Inflection option | Total number of nodes and mesh elements in model |
|------------------|------------------------|-------------------|--------------------------------------------------|
| Container-wall   | 2                      | 8 layers          | Nodes = 149740                                    |
| Water domain     | 2                      | -                 | Mesh elements = 147059                            |
| Air domain       | 3                      | -                 |                                                  |
| Heater           | 2                      | 10 layers         |                                                  |
In case 2 (with PCM), the number of mesh elements was doubled as more components were used. The number of layers used for the external wall, internal wall, and PCM container were also increased to ensure more accurate results. Table 3 and Figure 4 show the mesh size and the mesh used for case 2 (with PCM).

### Table 3. Mesh generation for case 2 (with PCM).

| Component name | Element mesh size, mm | Inflection option | Total number of nodes and mesh elements in model |
|----------------|-----------------------|-------------------|-----------------------------------------------|
| Container-wall | 2                     | 4 layers          | Nodes = 320983                                |
| Water          | 2                     | -                 | Mesh elements = 295043                        |
| Air1           | 3                     | -                 |                                              |
| PCM bottle     | 1                     | 8 layers          |                                              |
| PCM            | 0.6                   | 8 layers          |                                              |
2.2. **Numerical solution setup**

2.3. In order to determine the phase change PCM material conditions and energy, solidification and melting were enabled. Table 4 shows the generic model solver settings.

| Model                  | Settings                  |
|------------------------|----------------------------|
| Space                  | 2D space, planar           |
| solver, type           | pressure based             |
| velocity formulation   | relative                   |
| Time                   | transient                  |
| Gravity                | -9.81 m/s²                |
| energy enable          | enable                     |
| solidification and melting | enable                   |

The materials and thermo-physical properties of the elements forming the test model were taken from the Fluent database, Table 5 lists the specifications of the paraffin wax used.

| Properties                               | Value       |
|------------------------------------------|-------------|
| Melting temperature range                | 52          |
| Latent heat fusion                       | 230 kJ/kg   |
| Density (solid) ρ (s.ph.)                | 930 kg/m³   |
| Density (liquid) ρ (l.ph.)               | 830 kg/m³   |
| Specific heat (liquid) Cp̅pcm             | 2.4 kJ/kg.k |
| Specific heat (solid) Cp̅pcm              | 2.1 kJ/kg.k |
| Thermal conductivity, K̅pcm               | 0.25 w/m.k  |
| Viscosity µ                              | 0.031 kg/m.s|
| Thermal expansion                        | 11*10⁻³ l/k |
2.4. Assumptions and boundary conditions

1. The PCM material is homogenous and incompressible during both melting and solidification processes; the melt flow is thus considered laminar.
2. Each PCM container is filled completely with paraffin wax.
3. The volume change in PCM during phase change is ignored.
4. Hourly steady state, with Newtonian laminar fluid flow, is seen in the single-phase fluid (water).
5. The heat flux generated by the heater element is constant throughout the charging process.
6. Natural heat transfer convection occurs between the heater element and water, as well as between the water and the PCM containers, as no water moving forces act inside the tank; the low water speed offers proof of this assumption [20].
7. The heat convection currents of the water are of a laminar type, as the heater is a horizontal cylindrical object immersed in water. The Rayleigh number (Ra) =3.27 x 10^8 [20].
8. The system is thermally insulated.

The boundary conditions for the model elements are shown in Table 6.

Table 6. Boundary conditions for the model.

| Element zone | Adjacent cell zone | Momentum | Thermal |
|--------------|--------------------|----------|---------|
| Heater       | Water              | stationary wall |
|              |                    | no slip   | Heat flux = 11,000 W/m^2 for 2 hours (charging process) |
|              |                    |           | Heat flux = 0 W/m^2 for 22 hours (discharging process) |
| Wall-PCM Container | PCM domain | stationary wall |
|              |                   | no slip   | Heat flux = 0 W/m^2 |
| Insulation- wall | tank-wall | stationary wall |
|              |                   | no slip   | Wall thickness = 1 mm |

2.5. Numerical Solution Procedure

- All components of the numerical model were set at an initial temperature $T_i=24 \degree C$.
- The process of charging (heating) was set for the first two hours of operation, with the heat flux $=11,000$ W/m^2.
- The process of discharging the heat (cooling) took 22 hours of operation, with the heat flux $=0$ W/m^2.
- The temperature of the insulation wall is constant throughout all operation processes, with $T_{\text{insulation}} = 22 \degree C$.
- The water and PCM material temperatures were auto-saved every time step of 1 second, and time steps were collated every 300 seconds.
- Temperature distribution and liquid-fraction contours were recorded at different times.
- At the end of the simulation, data was transferred to an Excel spreadsheet.
2.6. Governing equations

The differential and algebraic equations for the required 2D-model can be written as in the equations below [19][21][22]:

- **Continuity Equation:**
  \[
  \frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} = 0
  \]  
  (1)

- **Momentum equation:**
  \[
  \text{X-direction } = - \frac{\partial P}{\partial x} + \frac{\partial (\rho u)}{\partial x} \cdot \frac{\partial u}{\partial x} + \frac{\partial (\rho v)}{\partial x} \cdot \frac{\partial v}{\partial y} = F_x
  \]  
  (2)

  \[
  \text{Y-direction } = - \frac{\partial P}{\partial y} + \frac{\partial (\rho u)}{\partial y} \cdot \frac{\partial u}{\partial y} + \frac{\partial (\rho v)}{\partial y} \cdot \frac{\partial v}{\partial y} = F_y
  \]  
  (3)

  \( F_x \) and \( F_y \) indicate external forces, such as buoyancy. In natural convection,

  \[ F = \rho g \]  
  (4)

  and the buoyancy force is:

  \[ F = \rho g \beta (T - T_{ref}) \]  
  (5)

  where \( g \), \( \beta \), and \( \rho \) are the acceleration of gravity, thermal expansion coefficient, and density of the liquid as a function of temperature, respectively.

- **Energy equation:**
  \[
  \text{Enthalpy formulation } \frac{\partial (H)}{\partial t} = \frac{\partial (Hu)}{\partial x} + \frac{\partial (Hv)}{\partial y} = - \frac{\partial P}{\partial x} \frac{\partial u}{\partial x} + \frac{\partial P}{\partial y} \frac{\partial v}{\partial y} + \frac{\partial (\mu u)}{\partial x} \frac{\partial u}{\partial x} + \frac{\partial (\mu u)}{\partial y} \frac{\partial u}{\partial y} \]  
  (6)

  where \( \mu \) and \( k \) are the viscosity and thermal conductivity of PCM, respectively, and \( h \) is the enthalpy per unit mass such that

  \[ \frac{\partial (h)}{\partial T} = \rho C_p \]  
  (7)

\[
\begin{align*}
    h &= \begin{cases} 
        C_{p_s} T & T < T_m \\
        C_p/T + (C_{p_s} - C_p) T_m + L & T \geq T_m
    \end{cases}
\end{align*}
\]  
(8)

The total enthalpy, \( H \), is a summation of the sensible enthalpy, \( h \), and latent enthalpy, \( \Delta H \):

\[ H = h + \Delta H \]  
(9)

where

\[ h = h_{ref} + \int_{T_{ref}}^{T} C_p \, dT \]  
(10)
\[ \Delta H = f \mathcal{L} \]  

(11)

where, \( h_{\text{ref}} \) is the sensible enthalpy of PCM at \( T_{\text{ref}} \), \( C_p \) is the specific heat at constant pressure, and \( \mathcal{L} \) represents the latent heat of the PCM.

Porosity is represented by the liquid fraction \( f \), which is defined as

\[
f = \begin{cases} 
0 & \text{if } T \leq T_s \\
\frac{T - T_s}{T_l - T_s} & \text{if } T_s \leq T \leq T_l \\
1 & \text{if } T \geq T_l 
\end{cases}
\]  

(12)

where, \( T_s \) and \( T_l \) refer to the solid and liquid temperatures of PCM, respectively. The local temperature is denoted by \( T \).

3. Results and discussions

The 24-hour simulation of charge and discharge operations in a two-dimensional water tank containing aluminum PCM containers heated by a constant heat flux showed the benefits of using PCM in the heat storage. It also allowed observation of the heat transfer process through the system, the behaviours of the PCM material during the charging and discharging processes, and the thermal conductivity implications.

The increase in temperature is a result of the heat flux generated from the heater placed at the bottom of the water tank, during the charging heat process that lasts for two hours. The heat transfer occurs via the natural water circulation inside the tank, with natural convection currents being generated when the layers of water surrounding the heater receive heat, expand thermally, reduce their density and rise vertically to the top, with the heavier and denser cold water layers falling due to gravity. The situation in case 2 (with PCM) differs, as the rows of PCM containers act as barriers to convection currents, and temperatures in the water layers below the first row of the PCM containers increase more rapidly than in the other water layers, especially in the center of the tank. This leads to an increase in the water layer temperature in contact with the bottom of the PCM containers in the lower row.

Figures 5 and 6 show the velocity vectors and velocity streamlines during the charging process (heat adding process) in the numerically modelled system for case 1 (without PCM) and case 2 (with PCM), respectively. This visualises the speed of water molecules during the heating process and shows the directions of the natural convection flow currents circulating inside the water tank.
Figure 5. (a) Velocity vectors (b) velocity streamline during the charging process for the numerical modeled system for case 1 (without PCM).

Figure 6: (a) Velocity vectors (b) velocity streamline during the charging process for the numerical modeled system for case 2 (with PCM).
Figures 7 and 8 show the temperature distribution contours for case 1 (without PCM) in the numerical modeled system.

Figure 7. Temperature distribution contours during the first hour of the charging process for case 1 (without PCM).

Figure 8: Temperature distribution contours during the charging process for case 1 (without PCM).
In this case, the convection currents run smoothly, and SHS is the only possibly thermal storage. At the end of the heating process, the maximum water temperature was 76.3 °C. After the heat flux is removed, the discharging process begins. The discharging process without PCM went smoothly, and at the end of the simulation process, the final water temperature was 39.7 °C, less than that required for home use.

Case 2 (with PCM) differed, as the rows of PCM containers acted as barriers to convection currents, increasing the water layer temperature in contact with the bottom of the PCM containers in the bottom row, especially in the center of the tank. The effect of the convection currents on both sides of the water tank was thus more apparent due to the gap between the inner side surface of the tank and the PCM containers being greater than the gap between the PCM containers, causing the hot water to move to the gap at the side of the tank and thus to warm up the sides of the containers facing the sides of the water tank before the other parts of the containers.

Figures 9 and 10 shows the temperature distribution contours for case 2 (with PCM) for the modelled system, during the charging and process.

Figure 9. Temperature distribution contours during the first hour of the charging process, for case 2 (with PCM).
In this case, both SHS and LHS offer possible forms of thermal storage. At the beginning of the heating period, the water temperature rises faster than that of the solid PCM, due to the poor thermal conductivity of the PCM; the thermal storage type is thus SHS for both water and PCM. When the PCM approaches its melting temperature ($T_{\text{melt}} = 52 \, ^\circ C$), the solid-liquid phase-change for PCM begins in the lower row of containers, after approximately 900 seconds, while the top row shows little sign of this process until 1,750 seconds into the simulation, and the material formed at that point is foamed rather than liquid phase.

Figure 11 shows the liquid-fraction contours for case 2 (with PCM) for the modelled system, during the charging process.
Figure 11. Liquid-fraction contours during the charging process for case 2 (with PCM)
The phase change process ends when the final portion of paraffin wax is melted in the container in the middle of the upper row, which occurs after approximately 6,200 seconds. Before this time, the thermal storage in the PCM is of LHS type, while after this, SHS is the only storage until the end of the heating process. The maximum water and PCM temperatures were 73.19 and 76.87 °C, respectively. The difference in maximum water temperature between the two cases (with and without PCM) is thus clearly due to the portion of thermal energy stored in the PCM material.

In case 2 (with PCM), the effect of adding the PCM material was also obvious when the PCM temperature approached solidification temperature ($T_{\text{solid}} = 51 ^\circ \text{C}$), as the latent heat stored in the PCM was released into the water. Figure 11 shows that the PCM changed its phase and returned to a solid-state approximately 75,000 seconds after the start of the simulation. At the end of the simulation process, the final temperatures were 48.22, and 50.12 °C for water and PCM respectively, and only a 1% fraction of the PCM did not solidify within the test period.

Figure 12 shows the liquid-fraction contours for case 2 (with PCM) for the modelled system, during the discharge process.
Figure 12. Liquid-fraction contours during the discharge process for case 2 (with PCM).

Figure 13 shows the numerical average temperatures for water and PCM with time for case 2 (with PCM).
Figure 13. Numerical average temperatures of water and PCM with time for case 2 (with PCM).

At the end of the heating process, the water temperature $T_{\text{maximum}}$ was 76.3 °C, while at the end of the simulation process, the final temperatures were 48.22 and 50.12 °C for water and PCM, respectively. Figure 14 shows that using PCM helps maintain the water temperature at a higher level, which implies that it could help maintain water at the required range for home use. The difference in the final water temperature between the two cases was 8.5 °C, a temperature gain of 21.46%.

Figure 14. Numerical average water temperature with time for cases with and without PCM.
4. Comparison with similar work

To check the results of this research, a comparison was made to a similar study by Shareef et al. (2020) [18]. Their experimental study was conducted in Iraq from 20 March to 20 April 2019, and the authors used a 49-litre iron tank containing 32 aluminum containers of 0.31 litre volume filled with 0.25 kg of paraffin wax, which melts at 52 °C. The volume of wax bottles thus represented 30% of the volume of water in the tank. A 1 kW electric heater was then used to heat the water for two hours. The results showed that the hot water temperature with paraffin wax was 7.5 °C higher than the water temperature in a similar tank with water alone. In the current study, a numerical model was constructed for similar boundary conditions, and the differences in the final water temperatures between the two cases (with and without PCM) was 8.5 °C. The temperature curves in Figures 15 and 16 show excellent agreement between the experimental reference [18] and the theoretical results, with a total error rate of no more than 5.17%.

Figure 15. Comparison between reference [18] and present work.

Figure 16. Average water temperature with and without PCM vs time for reference [18] and present work.

5. Conclusion

In the current study, a two-dimensional model of a water energy storage system integrated with a PCM material was designed and modelled using ANSYS Fluent. Two cases, with and without PCM, were investigated to examine the feasibility and utility of using PCM materials in such systems. The results showed that using PCM in water energy storage systems may be useful, as the final temperature in the case with PCM was 8.5 °C higher than that in the case without PCM, an increase of about 21.46%. This study thus highlights the advantages of using PCM materials in the field of heating systems, especially for domestic applications, based on the potential for saving energy in houses, thus reducing electric power demand and generating fewer carbon emissions.

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