Simulation analysis of Macro-Packed Phase Change Materials (MPPPCM) to reduce building energy use

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Abstract. This study sets up a zone-construction combination by constructing walls based on the classification of climates classified according to Korea's energy saving design standards and the heat paring rate standard of the wall. There are four climatic divisions, C1, C2, S, and J, and we have used representative climate data for each climate. The target building was a residential apartment, which is the main residential type of large cities in Korea and the world. In the set combination, PCM of TES system is placed indoors, and applied PCM is n-hexadecane, n-heptadecane, n-octadecane with phase change temperature of 20-28 °C corresponding to room temperature standard. Each PCM is set at 0.1% to 0.9% of the area of the building. We used Energy Plus 8.7, a building energy simulation, and analyzed the energy saving and economic efficiency of the building. Saved energy was 2.71% on average and we were able to save up to 4.56%. In addition, we conducted an economic analysis, saving an average of 3.42% and saving up to 7.48%.

1. Introduction

Heat Storage system is a method using two rows of sensible heat and latent heat. The sensible heat is heat related to the specific heat of a material and does not change the state of the material. Latent heat is the heat that accompanies a state change, which is the heat that is used to increase the temperature of the material when the state changes. In general, latent heat is more absolute than sensible heat, so it can save more heat energy. The material that uses this latent heat is called Phase Change Materials (PCM). Therefore, in this paper, we analyzed effects by applying PCM to buildings.

2. Simulation analysis

2.1. PCM properties

To apply PCM to buildings, PCM with appropriate phase change temperature should be selected and applied. When PCM is applied to outdoor or outdoor walls, it is important to consider the case of seasonally extreme temperatures. However, when applied to the indoor environment, the phase change between 20-28 °C the use of a PCM with a temperature allows the PCM to exhibit the latent heat performance through a phase change. Therefore, in this study, PCM with phase change temperature of 20-28 °C was selected and used for the study. Respectively. The selected PCM is paraffinic organic PCM, which is relatively inexpensive, has high calorific value, and has a low supercooling effect. Also, The physical properties of PCM are shown in Table 1.
Table 1. Thermo-physical properties of PCMs.

|            | Melting temperature (°C) | Thermal conductivity (W/m·K) | Latent Heat (J/g) | Density (g/m³) |
|------------|--------------------------|-----------------------------|-------------------|----------------|
| Hexa       | 18                       | 0.2                         | 231               | 0.88           |
| Hepta      | 22                       | 0.2                         | 200               | 0.88           |
| Octa       | 28                       | 0.2                         | 241               | 0.88           |

Nomenclature

| Symbol | Definition                                      |
|--------|-------------------------------------------------|
| 𝑅𝑇   | Total external wall thermal resistance (m²K/W)   |
| 𝑈    | Heat transmission coefficient (W/m²K)           |
| 𝜆𝑤   | Wall thermal conductivity (W/m)                 |
| 𝑇𝑤   | Wall thickness (m)                              |
| 𝜖𝑝mong | Specific heat of air                            |
| 𝜖𝑝PCM | Specific heat of PCM                            |
| 𝜌    | Density of air                                  |
| 𝜌PCM | Density of PCM                                  |
| 𝐻    | Enthalpy (J/kg)                                 |
| 𝐹    | Phase change rate                               |
| 𝐿    | Latent heat (J/g)                               |
| 𝑄 𝐻   | Heating energy requirement                      |
| 𝑄 𝐶  | Cooling energy requirement                      |

2.2. Building energy simulation

In this study, Chuncheon, Seoul, Busan, and Jeju, which correspond to ZC1 (Zone Center 1), ZC2 (Zone Center 2), ZS (Zone Southern), and ZJ (Zone Jeju), were selected as target areas. Each region is representative of the zone. Respectively. The target building is Korean residential apartment building. The wall of the building was classified into four categories according to the energy saving design standard, CC1 (Construction in Zone Center 1), CC2 (Construction in Zone Center 2), CS (Construction in Southern), CJ (Construction in Jeju) according to the heat flow rate according to each climate category. The heat transfer rate is calculated as follows.

\[
𝑅𝑇 = \sum_{k=1}^{n} \frac{𝑇𝑤}{𝜆𝑤} \\
𝑈 = \frac{1}{𝑅𝑇} 
\]

The wall of the building to be simulated is constructed by the above equation. (3), respectively. In order to apply PCM to the simulation, an enthalpy including latent heat and sensible heat must first be obtained. This Enthalpy method is based on an enthalpy formulation. [1] The equation for obtaining Enthalpy is as follows.

\[
𝐻 = \int_0^𝑇 \rho 𝐶𝑝𝑑𝑇 + ρ𝑙𝑙𝐿 
\]

The equation for obtaining the latent heat according to the phase change process is as follows. Equation (4)

\[
i_d = \begin{cases} 
0, & T < T_s \\
\frac{T - T_s}{ΔT}, & T_s + ΔT < T < T_s + ΔT \\
1, & T \geq T_s + ΔT 
\end{cases} 
\]

The process of phase change maintains a state in which solid and liquid coexist, and this represents latent heat. The enthalpy calculated using this equation is shown in Fig. 1 respectively. The application of PCM was increased 0.1% to 0.9% of the indoor area by 0.1% p. This is a classification for checking the energy-saving amount of PCM.
In this paper, the following demand equation is used to check the energy demand of the building. The setpoint temperature of the target building is 20 °C for heating and 26 °C for cooling. Setback temperatures are 18 °C and 28 °C respectively. Therefore, the cooling energy requirement and the heating energy requirement of the target building are calculated by the following equation.[2]

\[ Q_H = C_p \rho (20 - T_{\text{indoor}}) + L \quad \text{if} \quad T_{\text{indoor}} < 18^\circ C \]  \hspace{1cm} (5)

\[ Q_C = C_p \rho (26 - T_{\text{indoor}}) + L \quad \text{if} \quad T_{\text{indoor}} > 26^\circ C \]  \hspace{1cm} (6)

![Figure 1. Enthalpy values of PCM](image)

By adding the amount of latent heat of PCM to the existing required amount, it is possible to confirm energy demand by endothermic reaction and exothermic reaction according to phase change of PCM. The target structure of this study was an apartment building in Seoul, Korea. Its each floor consists of two houses, one staircase, and space for an elevator. The total area of one floor is 229.37 m², that of the house is 101.67 m², and the space for heating and cooling operations is 82.5 m². In the case of the internal HVAC system, heating was performed using a gas boiler and cooling was performed by an individual air-cooling system. Table 2 and Table 3 display more details of the target building.

### Table 2. Target building properties

| Building type | Apartment |
|---------------|-----------|
| Floor area (m²) | 229.37 |
| Number of floors | 20 |
| Azimuth | Southeast |
| Window | 20 mm multilayer glass |
| Heating equipment | Gas boiler / Gas |
| Air-conditioning | System air conditioner / Electric |
| Setpoint temperature | Heating (°C) 20, Cooling (°C) 26 |
Table 3. Target building properties Applied heat rate according to South Korea climatic classification

| Zone Part          | C1      | C2      | S       | J       |
|--------------------|---------|---------|---------|---------|
| Exterior wall      | 0.15    | 0.17    | 0.22    | 0.29    |
| Roof               | 0.15    | 0.17    | 0.22    | 0.25    |
| Ground floor       | 0.15    | 0.17    | 0.22    | 0.29    |
| Internal floor     | 0.9     | 1.0     | 1.2     | 1.6     |
| Window             |         |         |         |         |
| Door               |         |         |         |         |

3. Results and discussion

Fig. 1 shows the heating and cooling energy savings of Hexa, Hepta, and Octa in Chuncheon (ZC1-CC1), Seoul (ZC2-CC2), Busan (ZS-CS) and Jeju (ZJ-CJ). The results for heating energy reduction effect are as follows: The maximum heating energy reduction of Hexa was 2.00, 2.15, 2.01, and 2.23 kWh/m² for ZC1-CC1, ZC2-CC2, ZS-CS, and ZJ-CJ, respectively. The results using Hepta showed that the maximum heating energy reduction was measured at 2.32, 1.98, 1.88 and 1.95 kWh/m² for ZC1-CC1, ZC2-CC2, ZS-CS and ZJ-CJ, respectively. Furthermore, the maximum heating energy reduction of Octa was measured at 1.60, 1.26, 1.02, and 1.16 kWh/m². The most effective PCM for heating energy reduction was Hexa in ZC1-CC1 and ZC2-CC2 and Hepta in ZS-CS and ZJ-CJ. The maximum reductions measured in all cases were for 0.9% PCM. Compared with ZC1-CC1 and ZC2-CC2, ZS-CS and ZJ-CJ showed a heating energy reduction effect in Hepta with a relatively higher phase change temperature because the outdoor temperature differs depending on the climate conditions. Similarly to the results of the study by Yu et al. [3], the phase transition temperature of the optimized PCM increased linearly with the increase of the outdoor temperature. Additionally, the results of cooling energy reduction effect are as follows: The maximum cooling energy reduction for Hexa was 1.12, 1.06, 0.83, and 0.92 kWh/m² for ZC1-CC1, ZC2-CC2, ZS-CS, and ZJ-CJ, respectively. The Hepta results showed that the maximum cooling energy reduction was measured at 0.87, 1.09, 0.88, and 0.95 kWh/m² for ZC1-CC1, ZC2-CC2, ZS-CS, and ZJ-CJ, respectively, and the maximum cooling energy reduction of Octa was measured at 0.51, 0.76, 0.84, and 0.58 kWh/m², respectively. The most effective PCM for cooling energy reduction was also found to be Hexa in ZC1-CC1 and Hepta in ZC2-CC2, ZS-CS, and ZJ-CJ.

As the amount of PCM increases, the reduction in cooling energy increases because when the room temperature rises to such a degree that cooling is required, the heat remaining in the room moves to the PCM. Moreover, more PCMs can absorb more heat. However, the cooling energy reduction does not continue to diminish. [4] showed a decrease in energy consumption when PCM was applied to a radiation wall, and the greater the amount of PCM, the more energy consumption is reduced. However, the decline in energy consumption decreases.

Overall, the analysis showed that Octa reduced heating and cooling energy to a greater extent than Hexa and Hepta. The results show that the setpoints of heating and cooling for indoor comfort are closely related. According to Table 2, the target temperature of the building was 18-28 °C. In addition, heating energy is used when the temperature goes below the above-mentioned temperature range, and cooling energy is used when the temperature becomes higher than the temperature range. Octa means that the liquefaction reaction has hardly occurred since the phase change temperature is 28 °C. In other words, Octa could not show performance to latent heat. [5] showed that high temperature prevents PCM from losing stored heat, thus failing solidifying process.
Figure 2. Heating and cooling energy requirements according to application of each PCM (a) ZC1-CC1, (b) ZC2-CC2, (c) ZS-CS, and (d) ZJ-CJ

4. Conclusion
In this study, we divided the district into four zones by setting target areas according to the energy conservation design standards of Korea. A residential apartment building was chosen according to the heat paring rate standard for each region. Changes in cooling energy and heating energy requirements were confirmed on PCM application. We also confirmed the reduction in energy costs by analyzing the reduced demand. Table 4 shows the average, maximum, and minimum values of energy savings. In previous studies, PCM was applied only to the wall, roof, and floor; in contrast, we applied the PCM as a decorative element in this study.

Table 4. Reduction of energy demand

| Variables               | Unit | Minimum (%) | Maximum (%) | Average (%) |
|-------------------------|------|-------------|-------------|-------------|
| Energy demand reduction | %    | –0.6        | 4.56        | 2.71        |
| Energy cost reduction   | %    | –0.9        | 7.48        | 3.42        |

References
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