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Comparison Experiment on Floor Surface Temperature Change and Energy Consumption in PCM Radiant Heating System

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ABSTRACT

Purpose: The insulation performance of exterior walls, roofs, windows, etc. has improved with the strengthening of energy saving laws and has reached the current passive level. However, due to the increasing demand for achieving zero energy and improving indoor comfort, additional research is needed. Therefore, in this study, a comparative experiment was performed for the purpose of examining the phase change temperature of a phase change material (PCM) in order to apply it to an underfloor radiant heating system. **Method:** A mock-up affected by outdoor environmental conditions was constructed. Two mock-up rooms were equipped with a general radiant heating system and a PCM radiant heating system, respectively. PCMs with phase change temperatures of 44 and 35°C were used, and when the same room temperature conditions were maintained, the change in floor surface temperature and energy consumption of the rooms installed with the general and PCM systems were measured and compared. **Result:** As a result of the experiment, when the PCM was applied, the floor surface temperature was higher than that obtained with the general system. In particular, when the 44°C PCM was applied, the floor surface temperature was the highest. However, in terms of energy consumption and floor temperature maintenance performance, it was found that applying the 35°C PCM was the most advantageous.

KEYWORD

PCM 바닥복사난방시스템
상변화온도
Mock-up 실험

PCM Radiant Floor Heating System
Phase Change Temperature
Mock-up Experiment

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1. Introduction

1.1. Background and purpose of the study

Domestic building energy-related standards have improved the insulation performance of structures and windows, with remarkable energy-saving effects; as a result, the passive level has already been attained[1]. However, to achieve the 2050 carbon neutral and zero energy goals, efforts to improve the energy performance in various sectors and additional energy saving technologies are required. In addition, in a situation where the desire to improve the comfort of living spaces is increasing, it is necessary to develop systems that can secure not only energy performance but also comfort.

In floor radiation heating systems, the standard floor structure is applied to solve the problem of interlayer noise[2], but it does not provide a significant change in thermal performance compared to that of structures such as walls and roofs. Phase change materials (PCMs) are substances that can store or release latent heat energy in the process of change between the solid, liquid, and gas states to maintain temperature. PCMs can store 5 to 14 times more heat per unit volume than water, bricks, rocks, and other common materials[3-5]. When a PCM is used in a floor structure, it is possible to improve the comfort by maintaining a constant temperature of the indoor space, and it is also possible to save energy by lowering the peak load owing to the temperature delay effect[6][7].

In this study, a mock-up was constructed for the purpose of reviewing the appropriate phase change temperature when applying a PCM to a radiant heating system, and a comparative experiment was conducted with two phase change temperatures. Referring to previous studies[8][9], this work selected two types of PCM, n-docosane PCM with a phase change temperature of 44℃ and n-eicosane PCM with a phase change temperature of 35℃, and conducted an experiment to compare the floor temperature and energy consumption with those of a general radiant heating system.

1.2. Method and scope of the study

An outdoor mock-up laboratory affected by the actual change in external temperature was built, a general radiant floor heating system and a PCM radiant floor heating system were installed, and

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a comparative experiment was conducted. In the experiment, 44℃ and 35℃ PCMs were applied to the room where the PCM floor radiation heating system was installed, and the room temperature, change in floor surface temperature, and energy consumption were compared with those of the general floor radiation heating system installed in other rooms. Each experiment was measured for approximately 3 days, and the average outdoor temperature for them was similar at 6.4℃ and 6.3℃.

2. Mock-up room and PCM radiant heating system construction

2.1. Outdoor mock-up room construction

The outdoor mock-up used in the experiment consists of two rooms in the center of four rooms made of 100T prefabricated panels. The side walls are indirectly facing the outside air, and the front and rear walls are the walls facing the outside air directly. An additional 20mm of insulating material was added to the side walls to minimize heat input, and 250T extruded thermal insulation board (XPS) was installed on the inter-laboratory wall to minimize thermal bridges between laboratories. As shown in Fig. 1., the volume of each room is 13.2㎥, the floor area is 5.5㎡, and the height is 2.4m.

2.2. PCM radiant heating system construction

In the two mock-up rooms, a general floor structure was installed in Room 1 and a PCM floor structure was installed in Room 2, as shown in Fig. 2. In the case of the general floor structure, 20mm of sound insulation material for use between floors was installed on the concrete slab, a heating pipe was placed on it, and a 30mm floor plate made of mortar was installed. The PCM floor structure was similar to the general floor structure, but a PCM with aluminum packing was additionally installed at the bottom of the pipe on the sound insulation material.

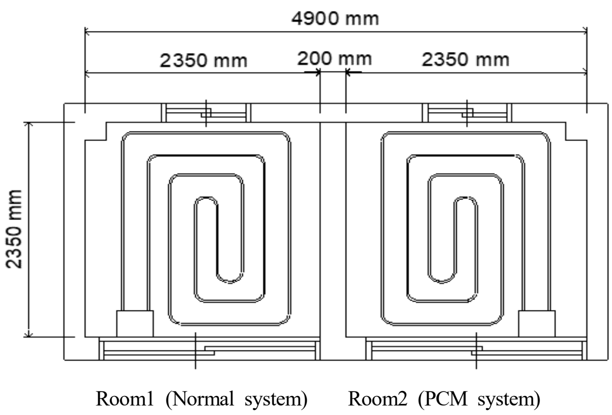

Fig. 1. Plan of mock-up room

Although gas-type hot water boilers are used in a general apartment house, an electric heating system, in which a heating wire is inserted in a pipe filled with a heating medium, was employed to facilitate quantitative comparison of energy consumption during the experiment. Because the heat is supplied through a heated pipe, the effect is the same as that of a conventional hot water boiler. The thickness of the heating pipe is 16mm, its length is 28m, the interval between pipes is 200mm, and in both chambers the same arrangement is installed.

2.3. PCM selection

PCM products with phase change temperatures of 44℃ and 35℃ were selected, as presented in Table 1. The 44℃ PCM is an n-docosane series with a phase change range of 40–43℃, and the 35℃ PCM is an n-eicosane series with a phase change range of 31–34℃[10][11]. The PCM was placed in an aluminum packing with good heat transfer and installed at the bottom of the pipe. For the comparison, the applied amount was the same for both substances, 20kg.

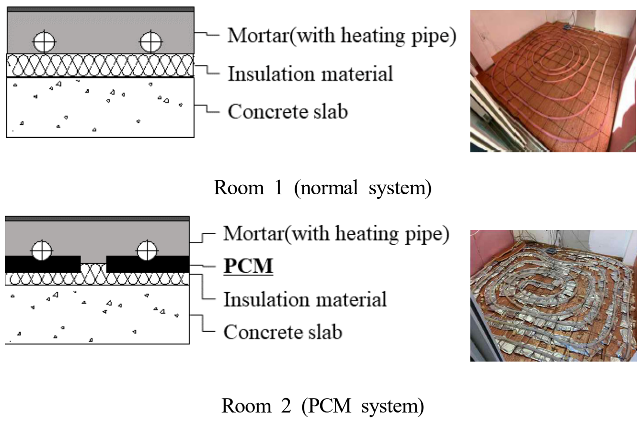

Fig. 2. Structure of mock-up room

Table 1. Properties of PCMs

PCM Type	44°C PCM	35°C PCM
Product	Sasol company, PARAFOL 22-95	Sasol company, PARAFOL 20Z
Chemical name	n-docosane	n-eicosane
Molecular Weight	310g/mol	282g/mol
Typical Latent Heat Capacity	63.9Wh/kg	57.8Wh/kg
Specific Heat Capacity	0.6Wh/kg	0.6Wh/kg
Heat Conductivity	0.2W/m·K	0.2W/m·K
Volume Expansion	12.5%	12.0%
Phase Change Temperature	40–43°C	31–34°C

3. Experiment

3.1. Experiment overview

The indoor temperature, floor surface temperature, and hot water temperature were measured so that the different changes in temperature in each room could be known.

For the measurement, T-type thermocouple sensors were installed in both Room 1 (general system) and Room 2 (PCM system), as shown in Fig. 3. To measure the indoor temperature, one sensor was installed at a height of 1.2m from the floor at the center of the room, and for the floor surface temperature, the average data was used after installing sensors at five points on the floor (floor center point, each center point divided into quarters).

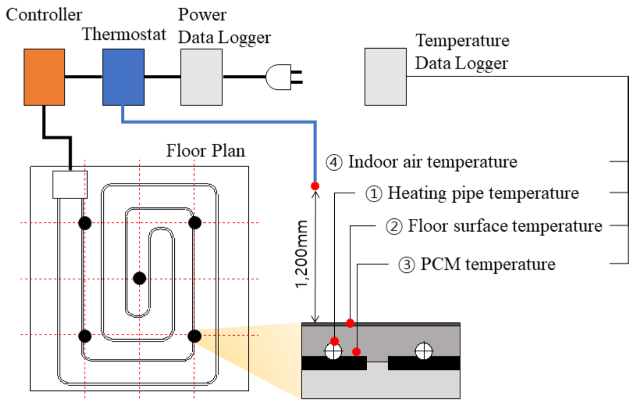

Fig. 3. Sensor location

Table 2. Experimental conditions for each case

Case	Underfloor heating system		Measurement period for analysis	Average outdoor temperature
	Room 1	Room 2		
Case-1	Normal system	44°C PCM system	2021.02.24. 20:00 ~ 2021.02.27. 20:00	6.4°C
Case-2	Normal system	35°C PCM system	2021.03.06. 20:00 ~ 2021.03.09. 20:00	6.3°C

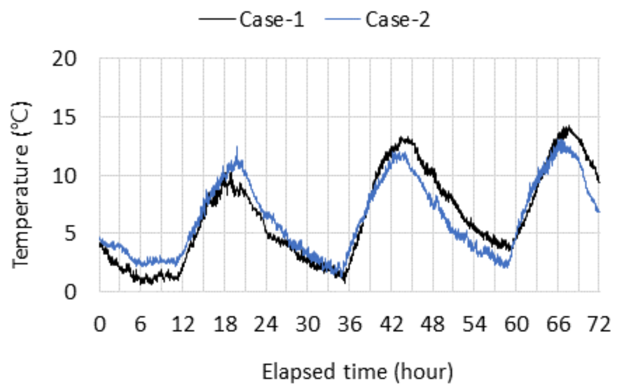

Fig. 4. Outdoor temperature in the measurement period for the analysis

Temperature data were collected at 1 min intervals using a data logger (GL820). Energy consumption data was collected at 1 min intervals by connecting the heating system and a power data logger (HPM-100A).

3.2. Experimental conditions for each case

The experimental case was divided into two as indicated in Table 2. In Case-1, a general radiant floor heating system and a 44℃ PCM radiant floor heating system were compared, and in Case-2, a general radiant floor heating system and a 35℃ PCM radiant floor heating system were compared.

The measurement was continuous for approximately 3 days in both Case-1 and Case-2, and the average outdoor temperature at this time was 6.4℃ for Case-1 and 6.3℃ for Case-2, as shown in Fig. 4.

During the experiment period, only the radiant floor heating system applied to each room was used for heating, and the operating range of the heating system was set to maintain the room temperature at 18-20℃. In other words, the heating system was activated when the room temperature dropped below 18℃, and it stopped when the temperature was above 20℃.

4. Results

4.1. Case-1 (44℃ PCM)

Case-1 is the result of a comparison experiment between a general radiant floor heating system (Room 1) and a radiant floor heating system in which the 44℃ PCM is applied (Room 2).

First, to compare the difference in floor surface temperature and energy consumption under the same indoor temperature condition, it was verified that the indoor temperature was similar. As a result of the measurement, as shown in Fig. 5., the room temperature range was similar, from 17.2 to 21.6℃ in Room 1 (normal) and from 16.9 to 22.1℃ in Room 2 (44℃ PCM). Although the heating temperature was set between 18 and 20℃, the interval was larger because there was a time difference

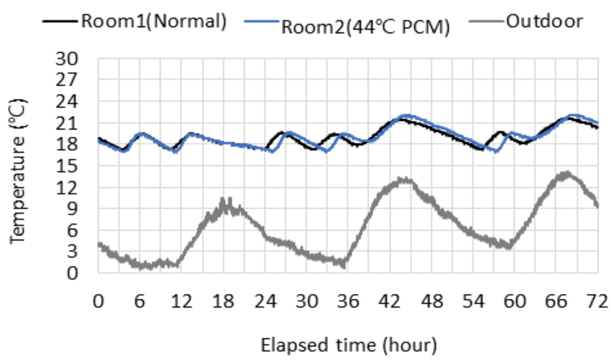

Fig. 5. Outdoor & indoor air temperature in Case-1

between the underfloor radiant heating and its effect on the indoor temperature after the heating was started or stopped. That is, when heating is started, the floor is heated first and then the indoor air is heated with this heat. Conversely, if the heating is stopped, the air temperature rises for a certain period of time due to the heat remaining on the floor. Moreover, when a PCM with high thermal storage performance is applied, the time delay becomes larger.

When the indoor temperature of the two rooms was in a similar range, the floor surface temperature showed a difference, as depicted in Fig. 6. The floor surface temperature range was 18.1–25.0℃ for Room 1 and 18.2–26.3℃ for Room 2. In other words, Room 2 was 1.7℃ higher at the highest temperature.

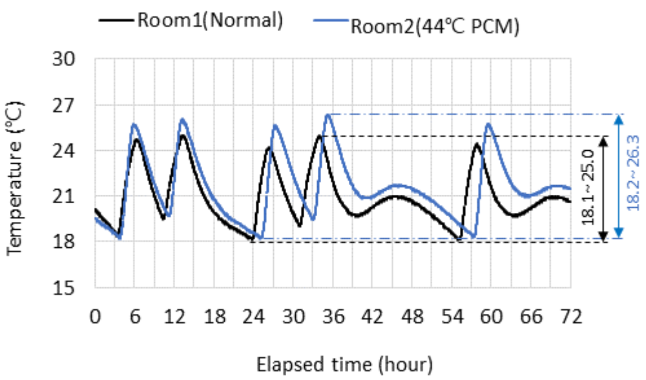

Fig. 6. Change in floor surface temperature in Case-1

Table 3. Comparison of average temperatures in Case-1

Average temperature of heating cycle	Room 1 (Normal) (①)	Room 2 (44°C PCM) (②)	Difference (② - ①)
Average of peak (increasing section)	24.0°C	25.1°C	1.1°C
Average of bottom (decreasing section)	18.9°C	19.3°C	0.4°C

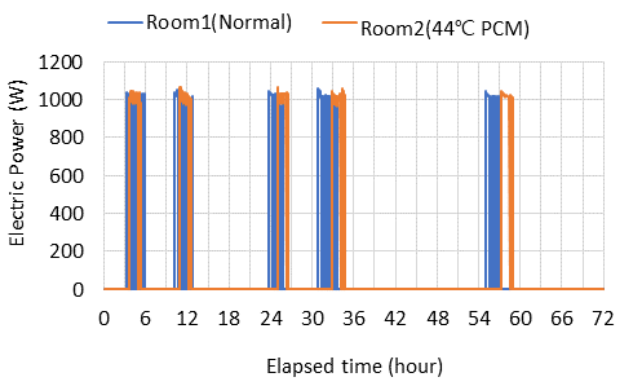

Fig. 7. Electric power variation in Case-1

Table 4. Energy consumption in Case-1

Heating system measurement result	Room 1 (Normal)	Room 2 (44°C PCM)	Saving rate
Heating operation time	481 min	478 min	0.62%
Total power consumption (3 days)	490.3kW	490.5kW	−0.04%

In addition, the results of comparing the highest temperature in the rising section and the lowest temperature in the falling section for each heating cycle of each room are presented in Table 3. Compared to Room 1, the highest temperature was 1.1℃ and the lowest temperature was 0.4℃ higher in Room 2; thus, Room 2 maintained a high temperature overall.

During the experiment period of approximately 3 days, the number of operations of the boiler was five times in both rooms, as indicated in Fig. 7. and Table 4. The operating time was 481 min for Room 1 and 478 min for Room 2. It decreased by 0.62% in Room 2, but the power consumption increased by 0.04%.

4.2. Case-2 (35℃ PCM)

Case-2 is an experiment comparing the general floor radiant heating system (Room 1) and the floor radiant heating system (Room 2) with the 35℃ PCM, and as shown in Fig. 8., the range of change in room temperature was similar, 17.2–21.7℃ in Room 1 (general) and 17.1–21.6℃ in Room 2 (35℃ PCM).

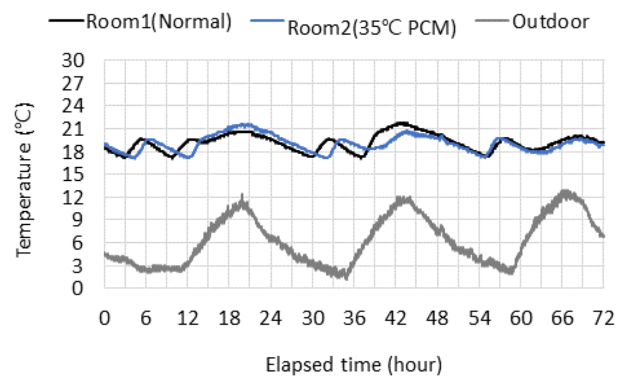

Fig. 8. Outdoor and indoor air temperature in Case-2

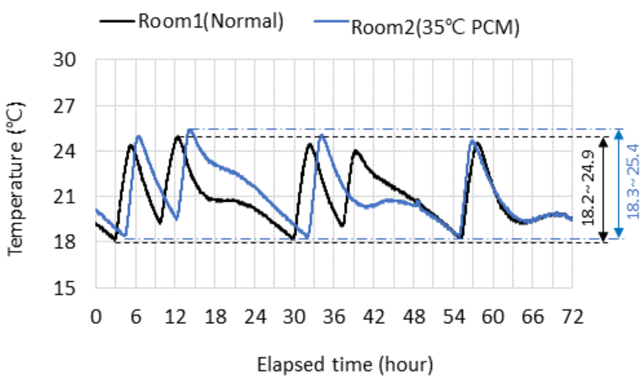

Fig. 9. Floor surface temperature in Case-2

When the indoor temperatures of the two rooms were similar, the change in the floor surface temperature ranged from 18.2 to 24.9℃ for Room 1 and from 18.3 to 25.4℃ for Room 2, as shown in Fig. 9. The minimum temperature was similar, and the maximum temperature was 0.5℃ higher in Room 2.

Further, as a result of comparing the highest temperature in the rising section and the lowest temperature in the falling section for each heating cycle of each room, in Room 2 the temperature was 0.6℃ higher in both the highest and lowest temperatures, as indicated in Table 5.

During the experiment period, as presented in Fig. 10. and Table 6., the number of operations of the boiler was five times in Room 1 and four times in Room 2. As the number of operations of Room 2 decreased, the operating time decreased by 5.47% in Room 2, from 413 min in Room 1 to 388 min in Room 2. Power consumption also decreased by 6.05%. The reason for this result is that the heating was not operated during the daytime when the external temperature rose due to the temperature delay effect when the 35℃ PCM was applied.

Table 5. Comparison of average temperatures in Case-2

Average temperature of heating cycle	Room 1 (Normal) (①)	Room 2 (35°C PCM) (②)	Difference (② - ①)
Average of peak (increasing section)	24.4°C	25.0°C	0.6°C
Average of bottom (decreasing section)	18.9°C	19.4°C	0.6°C

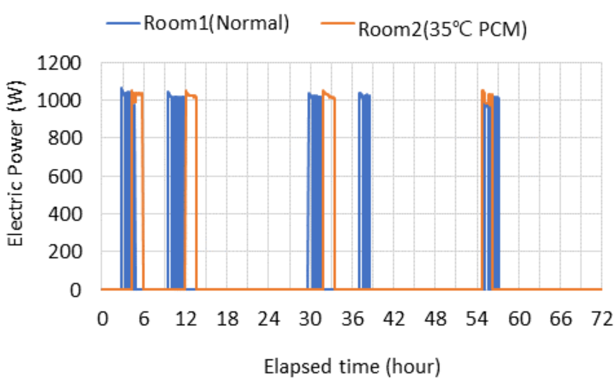

Fig. 10. Electric Power for Case-2

Table 6. Energy consumption in Case-2

Heating system measurement result	Room 1 (Normal)	Room 2 (35°C PCM)	Saving rate
Heating operation time	413 min	388 min	5.47%
Total power consumption (3 days)	425.8kW	402.5kW	6.05%

4.3. Sub-conclusion

In this study, general and PCM radiant floor heating systems were applied to the same two mock-up laboratory floors affected by the external environment, and the heating systems were operated to maintain a constant indoor temperature. The floor surface and room temperatures and energy consumptions were compared.

PCMs with phase change temperatures of 44℃ and 35℃ were applied, and each case was compared with the general radiant floor heating system. The results of the experiment are presented in Table 7. In Case-1, when the 44℃ PCM was applied, the floor surface temperature was 0.4-1.1℃ higher than that with the general system. However, the power consumption decreased by 0.04%, a very similar result.

In Case-2, when the 35℃ PCM was applied, the floor surface temperature was 0.6℃ higher than that with the general system. In addition, the power consumption was reduced by 6.05% compared to the general system.

Table 7. Comparison of experimental results when PCM is appied

Result data	Case-1 (normal vs. 44°C)	Case-2 (normal vs. 35°C)
Increase in temperature of floor surface	0.4–1.1°C	0.6°C
Energy saving rate	−0.04%	6.05%

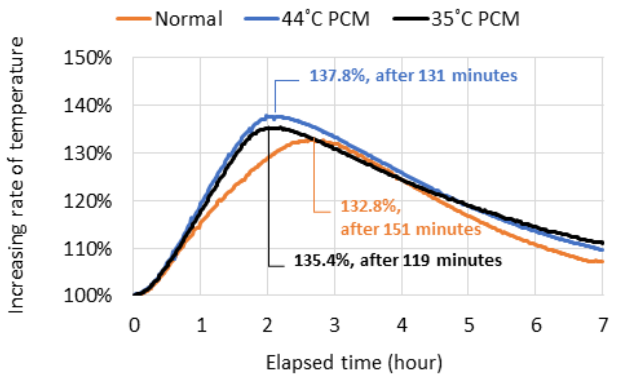

Fig. 11. Variation in floor surface temperature for each system

Table 8. Comparison of systems

Result data	Normal system	44°C PCM system	35°C PCM system
Peak temperature increase rate (from start)	132.8%	137.8% (▲5.0%)	135.4% (▲2.6%)
End temperature increase rate (from start)	110.6%	113.5% (▲3.5%)	114.4% (▲4.4%)
Time to reach peak	151 min	131 min (▼17.6%)	119 min (▼25.2%)
Temperature decrease rate per hour (from peak)	−6.6%	−6.4%	−5.2%

Further, a relative comparison of the change in floor surface temperature by system based on the experimental results for each case is presented in Fig. 11. and Table 8. To compare the data used for this purpose on the same scale, only the change in temperature at night, when there is no effect of solar radiation, was extracted and averaged. Then, for a relative comparison, it was converted from the starting temperature to the rate of increase in temperature per hour.

As a result, the highest floor temperature after the heating operation was in the following order: 44℃ PCM (137.8%) 〉 35℃ PCM (135.4%) 〉 general system (132.8%). Thus, it was confirmed that when a PCM is applied, a relatively higher temperature is attained than that obtained with general systems. In addition, even after 7h, the floor surface temperature was in the following order: 35℃ PCM (114.4%) 〉 44℃ PCM (113.5%) 〉 general system (110.6%). The application of 35℃ PCM resulted in the highest temperature.

The reaction time required for the floor surface to reach the maximum temperature was the fastest when applying the 35℃ PCM, with the following order: general system (151 min) 〉 44℃ PCM (131 min) 〉 35℃ PCM (119 min). In addition, when the boiler was stopped after reaching the highest temperature, the rate of reduction in temperature per hour was found to be in the following order: general system (−6.6%) 〉 44℃ PCM (−6.4%) 〉 35℃ PCM (−5.2%).

5. Conclusion

In this study of floor radiant heating systems, a mock-up exposed to actual winter outdoor air conditions was constructed and a comparative test was conducted based on PCMs with two phase change temperatures (44 and 35℃). The experimental results can be summarized as follows.

1) Compared to the general system, the floor surface temperature was 0.4–1.1℃ higher with the 44℃ PCM and 0.6℃ higher with the 35℃ PCM, confirming that the PCM maintained a higher temperature.
2) In terms of energy consumption, when the 35℃ PCM was applied, there was an energy saving of approximately 6% compared to the general system.
3) As a result of comparing the general system with the 44 and 35℃ PCMs, the maximum temperature of the floor surface was the highest when the 44℃ PCM was applied, and it was found that the 35℃ PCM maintained the floor heat for the longest time.

This study was based on a mock-up affected by the actual external environment rather than a laboratory environment. Thus, it was possible to design a PCM radiant floor heating system that can be applied to the actual field, to secure experimental data, and to provide review data for each PCM temperature condition. However, given that the experimental period was short and it was affected by low temperature and solar radiation, additional review is necessary. Therefore, in the future, based on long-term experiments, additional studies on temperature change, energy consumption, and thermal comfort under a lower winter temperature condition will be conducted, and an optimal control method will be proposed in consideration of the temperature delay effect of PCMs.

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