Experimental Study on Thermal Performance of Pre-formed Thin Heating Floor Filled with Shaped PCM

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Abstract. A shape-stabilized phase change material (PCM) with high-density polyethylene was prepared as the supporting material to be added to a pre-fabricated light and dry-type heating floor. A system for underfloor heating experiments was set up in the laboratory to test the effects of average supply and return water temperatures and different temperature differences on the thermal performance of two floor heating systems under 10 different operating conditions, respectively. The results show that the surface heat-flux density of a phase change floor (PCF) is higher than that of an ordinary one at the stable stage. The proportion of heat transfer to the heating room is about 13% higher in the phase change system compared to the normal system, and the heat loss is reduced by more than 10%. At the cooling stage, the surface temperature of PCF decreases slowly, compared to the rapid decrease of the ordinary one.

1. Introduction

At present, China is undergoing a period of prodigious development, and its energy challenges are becoming increasingly more prominent. The energy conservation is important in the overall energy saving plan. Nowadays, radiant-heating floor systems, featuring low temperature and hot water, are very popular globally. They can raise the floor temperature and decrease the upper temperature to realize the healthy concept of “warm feet and cool roof,” in contrast to a traditional radiator convection heating system. In addition, the research on phase change materials is progressing rapidly [1, 2]. Adding phase-change materials (PCMs) to flooring can absorb or release heat in large amounts with a constant temperature and limited temperature fluctuation. As a result, the system can store/release energy during the night/day. based on the power price to create a comfortable and energy-saving living environment.

Some scholars have conducted related studies. Sun [3] et al. experimentally studied the heat transfer mechanism of the PCM in the high-density polyethylene rectangular panel during the melting process. [4] Kenisarin et al. analyzed the latest technology for integrating PCM into building structures for passive thermal control. Wang [5] et al. reported the application of PCM to disaster relief prefabricated temporary houses, and two different designs of applied PCM were experimentally investigated. Paraffin chain alkanes were applied by Cerón [6] et al. as PCMs to prepare a PCM composite floor at a PC temperature of 20°C, and the surface temperature of the composite floor was studied by experimental tests and numerical simulations. A composite PCM with 85% paraffin was added to hollow concrete floors by Royon [7] et al. to study their thermal properties by experimental and simulation methods. Anzhong [8] et al. produced composite granular PC granular material with lauric acid and myristic acid as the PCM and SiO2 as the carrier. A PC gypsum mortar was prepared, and the heat storage/release properties of the PC mortar and an ordinary were studied experimentally.
In this work, a new pre-fabricated PC heating floor with PCM added was prepared, which is both light and thin. Dry laying with no cement mortar was applied and compared with the ordinary floor without PCM. The model was tested for each group of experiments by being heated for 2–3 h, kept stable for 8 h, and then cooled for 8 h. The thermal performance of the two types of flooring was compared in the stabilisation and cooling phases at different average, supply and return water temperatures.

2. Experimental Scheme

2.1 Experimental System
The dimensions of the laboratory room for this underfloor heating system are 6.00×2.80×2.60 m (L×W×H). The wall of North is installed with a single steel window measuring 1.74×1.62 m, directly facing the exterior environment. The South is equipped with a single-layer door of glass to separate the test room from the operations room.

2.2 Experimental system and equipment selection
The equipment models selected for the test are shown in Table 1.

| No. | Equipment Name                  | Model No.   | Working Conditions | Purpose                                      |
|-----|--------------------------------|-------------|--------------------|----------------------------------------------|
| 1   | Pump                           | 15WBX0.6-10| 0.6 m³/h           | Cyclic power provision                       |
| 2   | Converter                      | TDGC2-2     | 0.1 V              | Supply/return water-temperature adjustment   |
| 3   | Electromagnetic flowmeter      | 7ME5038-2AA12-1AA0 | 0.0001 m³/h | System water-flow testing                   |
| 4   | Platinum-resistance temperature sensor | PT100       | 0.1°C             | Supply- and return-water temperature testing |
| 5   | Infrared thermal imager        | TH9100      | 0°C–250°C          | Locate surface of floor and tube between tube position |
| 6   | Data-collection meter          | Agilent 34970A | −100°C–400°C  | Record temperature of measuring point        |
| 7   | Automatic control water distiller | DZ-20     | 0.02 m³/h         | Produce distilled water                      |
| 8   | Pressure gauge                 | MC03820348  | 0.001 MPa          | Test system pressure                         |
| 9   | Multipoint heat-flow meter     | HFM-215     | 10–3000 W/m²      | Test floor surface heat-flux density         |

2.3 Construction of PC floor
The shaped PCM was poured into the positioning plate channel of the PC floor, after which natural cooling and solidification formed a dry PC heating floor. Figure 1 shows the specific structure.

PCM (48# solid paraffin-liquid paraffin) is molten with high density polyethylene in a 7:3 ratio by mass to produce the phase change material used.
2.4 Experimental Principle and Measurement Point Arrangement

The working principle of the system is shown. The distilled water is heated by electric heating and then filtered through the Y-type filter, and is drawn into the water separator due to the pressure of the booster pump. Then, driven by water separator, PCF and other two different circuits will enter the water collector after cooling, then returned to the water tank through a Y-strainer. (Figure. 2).

The test room is located in a room of the No. 2 Experimental Building, Beijing University of Civil Engineering and Architecture, and measures 6.00×2.80×2.60 m (L×W×H). The room, an ordinary reinforced concrete structure, is installed with ordinary radiators for heating on the upstairs, downstairs and East sides, and toilet is located on the west side. The East and West walls of the room are interior ones. The wall of North is installed with a single steel window measuring 1.74×1.62 m, directly facing the exterior environment. The South is equipped with a single-layer door of glass to separate the test room from the operations room.

The experimental system divides the PCF and the common one into four areas. In each zone, a temperature measurement point was selected between the highest and lowest point of tube. The setting of measurement points on wall and window structures depended on the orientation of the envelope. Indoor-air measurement points were placed in the middle of the room. The starting distance between them and the ground is 0.15 meters, with a continuous increment of 0.35 m per time for 6 times, and the roof is 2.60 m. The multi-point heat flow meter has a total of 5 measuring points, which are evenly distributed throughout the laboratory. The measurement points are set at ground and roof level under the PCF. The temperature measuring point in the room below is approximately 0.75 m above the floor. Pressure and temperature measurements are set at the inlet of the water separator 10 and at the outlet of the water collector 11 (The measurement points in the experimental room are set as in Figure 3).
3. Experimental Processes and Data Processing

In this experiment, the supply/return water temperature for normal flooring and PCF was approximately 35-55°C in 5°C increments. And the temperature difference was 5°C and 10°C respectively. The heating performance was tested by heating the model for 2~3 h, keeping it stable for 8 h, and then cooling for 8 h. The temperature measured in this experiment was calculated and processed by a series of formulas to obtain the distribution of thermal parameters under different supply/return water average temperatures and different temperature differences of supply/return water.

(1) Calculate the average temperature of the floor surface according to equation (1).

\[
\bar{t}_{pj} = \frac{\sum_{l=1}^{n} t_{igd} + 2 \times \sum_{l=1}^{n} t_{igj}}{2n}
\]

where \(t_{pj}\) is the average temperature of the thermosphere, ºC; \(t_{igd}\) the tube top temperature, ºC; \(t_{igj}\) the inter-tube temperature, ºC; \(n = 4\).

(2) The upward heat dissipation from the floor surface was calculated as follows:

\[
q = q_e + q_r = 2.13 \times (t_{pj} - t_n)^{3.1} + 4.98 \times 10^{-8} \left( T_{pj}^4 - T_{gf}^4 \right)
\]

(3) The downward heat dissipation from the floor surface was calculated as follows:

\[
q = q_d + q_r = 0.134 \times (t_{pj} - t_n)^{2.5} + 4.98 \times 10^{-8} \left( T_{pj}^4 - T_{gf}^4 \right)
\]

where \(q_e\) is the upward convective heat-flux density on the surface, W/m²; \(q_r\) the radiation heat transfer per unit area, W/m²; \(t_n\) the average indoor temperature, ºC; \(T_{pj}\) the open surface temperature of the heating surface, \(T_{pj} = t_{pj} + 273, K\); and \(T_{gf}\) the weighted average temperature of the unheated layer, \(T_{gf} = t_{gf} + 273, K\).

4. Experimental Results and Analysis in the Stable Stage

4.1 Temperature of the Floor Surface

The thermal parameters of ordinary floor and PCF were tested separately under different supply/return-water average temperatures and different temperature differences. From Fig. 4, the calculated processing results of the floor surface temperature under different working conditions can be obtained. According to which the floor surface temperature of the ordinary floor and PCF increases with increasing average temperature of supply & return-water during the stable heating stage. However, the temperature difference between the supply and return water has a certain influence on the floor temperature. Under the same average temperature conditions of the return water, the temperature difference between the supply/return water is larger, and the floor surface temperature is smaller. Under the conditions of the same average temperature and temperature difference of supply & return-water, the surface temperature of the PCF is slightly lower than that of the ordinary floor.
Figure 4. Floor surface temperature of ordinary floor and PC floor under different working conditions

Figure 5. Upward heat-flux density on the floor surface of ordinary floor and PC floor under different conditions

4.2 Upward Heat-flux Density on Floor Surface

Using a formula to calculate and process the measured thermal parameters, the upward heat-flux density of the floor surface of the ordinary and PCF under different working conditions at the stable stage is shown in Fig. 5, which suggests that the upward heat-flux density of the ordinary and PCF surfaces increases with increasing average temperature of the supply & return-water at the stable heating stage. Under the conditions of same supply/return-water temperatures, the upward heat-flux density of the PCF surface is higher than that of the ordinary floor surface, ignoring the effects of temperature differences.

4.3 Heat-transfer Ratio of Floor Surface Upward and Downward

The heat dissipation from the floor surface to the heating room and the thermal-loss ratio from the floor to the lower floor are compared and analyzed in the stable stage between the ordinary and PCFs; the results are shown in Tables 2 and 3 for 5 °C and 10 °C temperature differences, respectively.

| Water temperature (°C) | Floor  | Total heat (W/m²) | Upward heat dissipation (W/m²) | Upward heat dissipation ratio (%) | Downward heat loss (W/m²) | Heat-loss ratio (%) |
|------------------------|--------|-------------------|-----------------------------|----------------------------------|-------------------------|-------------------|
| 35                     | ordinary | 61.59             | 52.42                       | 85.10                            | 9.17                    | 14.9              |
|                        | PCF     | 56.19             | 55.24                       | 98.31                            | 0.95                    | 1.69              |
| 40                     | ordinary | 73.43             | 63.86                       | 86.98                            | 9.56                    | 13.02             |
|                        | PCF     | 69.01             | 67.66                       | 98.04                            | 1.35                    | 1.96              |
| 45                     | ordinary | 99.8              | 87.55                       | 87.73                            | 12.25                   | 12.27             |
|                        | PCF     | 97.80             | 97.56                       | 99.75                            | 0.25                    | 0.25              |
| 50                     | ordinary | 109.39            | 97.05                       | 88.71                            | 12.35                   | 11.29             |
|                        | PCF     | 103.39            | 102.30                      | 98.95                            | 1.09                    | 1.05              |
| 55                     | ordinary | 133.16            | 118.69                      | 89.14                            | 14.46                   | 10.86             |
|                        | PCF     | 119.32            | 117.90                      | 98.81                            | 1.42                    | 1.19              |

Table 2. Ratio of upward and downward heat transfer between ordinary and PC floors at 5 °C temperature difference.
Table 3. Ratio of upward and downward heat transfer between ordinary and PC floors at 10 °C temperature difference.

| Water temperature (°C) | Floor  | Total heat (W/m²) | Upward heat dissipation (W/m²) | Upward heat dissipation ratio (%) | Downward heat loss (W/m²) | Heat-loss ratio (%) |
|------------------------|--------|-------------------|-------------------------------|---------------------------------|--------------------------|--------------------|
| 35 ordinary            | 55.27  | 46.82             | 84.72                         | 8.44                            | 15.28                    |
| PCF                    | 45.88  | 45.24             | 98.61                         | 0.64                            | 1.39                     |
| 40 ordinary            | 63.91  | 54.47             | 85.23                         | 9.45                            | 14.77                    |
| PCF                    | 61.61  | 61.20             | 99.33                         | 0.41                            | 0.67                     |
| 45 ordinary            | 89.80  | 77.95             | 86.81                         | 11.84                           | 13.19                    |
| PCF                    | 82.72  | 81.21             | 98.18                         | 1.5                             | 1.82                     |
| 50 ordinary            | 105.48 | 92.25             | 87.46                         | 13.23                           | 12.54                    |
| PCF                    | 91.65  | 91.10             | 99.41                         | 0.54                            | 0.59                     |
| 55 ordinary            | 130.19 | 115.58            | 88.78                         | 14.61                           | 11.22                    |
| PCF                    | 110.20 | 109.69            | 99.53                         | 0.52                            | 0.47                     |

It can be seen from Tables 2 and 3 that for temperature differences below 5°C and below 10°C, the upward heat-transfer ratio of the ordinary floor is much smaller than that of the PCF, while the downward heat loss of the ordinary floor is much larger than that of PCF. The heat-transfer ratio of the ordinary-floor heating system to the heating room is above 85%, and the heat loss of the lower floor room is less than 15%. The heat-transfer ratio of the PCF heating system to the heating room is above 98%, and the heat loss of the lower floor room is less than 2%. There is almost no heat loss in the heat dissipation of PCF heating. All the heat is transferred to the heating room, indicating that the PCF has a good heat-storage function.

5. Experimental Results and Analysis in Cooling Stage

The system was cooled for 8 h after 8 h of stable heating, and the surface temperature of the floor tested under 10 different conditions; the results are shown in Figs. 6–10.
Analysis of the above figures show that after the heat storage is over, the temperature curves of the ordinary and PCFs exhibited a downward trend. At the time the heating was stopped, the surface temperature of the ordinary floor is higher than that of the PCF. However, as the time passed, the temperature growth rate of PCF is faster than that of ordinary floor with the latter decreasing rapidly. This indicates that adding shaped PCM into the floor can store and release heat during the period of system heating and cooling, with limited temperature fluctuation. Moreover, the PCF can store heat. Under the conditions of the same average temperature of supply & return-water, the higher temperature difference between supply & return-water will lead to the higher difference between the ordinary and PCFs in surface temperature at time "0" in the figures.

6. Conclusions
(1) Once the heating has stabilised, the surface heat flow density of PCF and the normal flooring increases with the average temperature of the heating medium. The greater the temperature difference
between the heating media, the lower the average surface temperature of the floor when the average supply and return water temperature conditions are the same. When both the average temperature of the heating medium and the temperature difference are the same, the surface temperature of PCF is slightly lower than that of ordinary flooring, while the rising heat flow density of PCF is higher.

2) At the cooling stage, the indoor temperature of the ordinary floor decreased more than that of the PCF, suggesting that the PCF stored and released heat during the experiment.

3) The heat transfer ratio of the common floor to the experimental room is above 85% and the heat loss from downward heat transfer is no more than 15%, values that are better than those of conventional wet floor radiant heating systems. The PCF systems have a heat transfer rate of over 98% to the plus test room, and the heat loss of the lower floor room was above 2%. Thus, it could be seen that there was almost no heat loss in PCF heating, so the PCF exhibited a good heat-storage function.

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References
[1] Yang L, Jin X, Zhang Y, et al. (2020) Recent development on heat transfer and various applications of phase-change materials. Journal of Cleaner Production
[2] Nazir H, Batool M, Osorio F J B, et al. (2019) Recent developments in phase change materials for energy storage applications: A review. International Journal of Heat and Mass Transfer, 129(2):491-523.
[3] Sun X, Chu Y, Mo Y, et al. (2018) Experimental investigations on the heat transfer of melting phase change material (PCM). Energy Procedia, 152:186-191.
[4] Kenisarin M, Mahkamov K. (2016) Passive thermal control in residential buildings using phase change materials. Renewable & Sustainable Energy Reviews, 55:371-398.
[5] Wang C, Huang X, Deng S, et al. (2018) An experimental study on applying PCMs to disaster-relief prefabricated temporary houses for improving internal thermal environment in summer. Energy & Buildings, 179:301-310.
[6] Cerón I, Neila J, Khayet M. (2011) Experimental Tile with Phase Change Materials (PCM) for Building Use. Energy and Building, 43:1869-1874.
[7] Royon L, Karim L, Bontemps A. (2013) Thermal energy storage and release of a new component with PCM for integration in floors for thermal management of buildings. Energy & Buildings, 63(8):29-35.
[8] Deng A, Zhuang C, Li S, et al. (2010) Study on composite phase change mortar filling materials for floor heating systems [J]. Journal of Building Materials, 13 (2): 162-164.