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Multiscale Finite Element Modeling of the Effect of Macro-Encapsulated Phase-Change Materials on the Thermal Performance of Hydronic Floor Heating Systems

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Abstract: Phase-change materials (PCMs) are commonly employed in building service equipment to regulate indoor temperatures and reduce energy consumption. This study conducted multi-scale finite element modeling to analyze the steady-state and dynamic thermal behavior of a hydronic radiant floor heating system integrated with macro-encapsulated PCMs. It predicted performance values for hydronic floor heating with and without macro-encapsulated PCMs. The study assessed the impact of the PCM volume fraction, heating water temperature, capsule thermal conductivity, and shape on the thermal performance of hydronic floor heating through various finite element models. The predictive capability of the finite element model was validated using experimental data, showing good agreement. Although the inclusion of PCMs lowered the floor temperature, it improved temperature distribution and retained heat when the system was inactive. The PCM volume fraction significantly influenced the performance of the hydronic floor. However, the shape of the macro-encapsulated PCM and thermal conductivity of the shell had minimal effects in the studied case. For instance, increasing the thermal conductivity of the shell of the PCM capsule fifty times from 0.3 to 15 W m⁻¹ K⁻¹ resulted in an increase in surface temperature by 1.2 °C.

Keywords: finite element modeling; thermal analysis; macro-encapsulated; phase-change material; hydronic radiant floor



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1. Introduction

According to the 2013 report “Transition to Sustainable Buildings: Strategies and Opportunities to 2050”, nearly 60% of the electricity consumed in residential buildings is for water heating and space heating/cooling [1]. Consequently, interest is growing in developing heating/cooling systems that are economically and environmentally advantageous. Thermal storage emerges as a promising technology to reduce energy use in buildings. This concept, based on the ancient practice of storing thermal energy from daytime for use in the evening using stones that absorb solar heat during the day and release it at night, has gained widespread adoption in residential and commercial settings [2]. Phase-change materials (PCMs) are employed in various energy applications because of their superior ability to store thermal energy as latent heat. Numerous studies have explored the integration of PCMs into various building and construction materials, such as concrete [3–5], bricks [6–10], tiles [11], building plaster [12–14], and wallboards [15,16]. These studies have investigated their potential to regulate indoor temperature and reduce energy consumption.

Extensive experimental and computational investigations have explored the integration of PCMs into radiant flooring. Hydronic radiant floor systems are economically and environmentally advantageous, as they operate at lower water temperatures than other systems [16]. These systems are also compatible with solar water heaters, which can reduce electricity costs. Incorporating PCMs into radiant floor heating systems enhances their energy storage capacity, allowing them to accumulate solar energy during the day and

release it at night. Moreover, it can shift energy usage from high-demand to low-demand periods [17]. The PCM stores thermal energy during the heating phase and releases it during the non-heating phase. Cheng et al. [18] investigated how the thermal conductivity of PCMs affects radiant flooring efficiency. Zhou and He [19] conducted experiments on various PCMs and pipes, while Zhao et al. [20] and González and Prieto [21] conducted numerical studies to predict the effects of PCM placement on system performance. However, in these studies, the PCMs were kept inside large containers, which hindered heat transfer between the concrete and PCMs. Consequently, several studies [22–24] have recommended using smaller encapsulated PCMs. Li et al. [25] examined the thermal properties of mortar with microencapsulated PCMs used for hydronic floor heating; however, they did not investigate the performance of the hydronic radiant floor. This study investigates the performance of hydronic radiant floors with macro-encapsulated PCMs using a multiscale finite element (FE) modeling approach. It also examines the effects of macro capsule shape, thermal conductivity, PCM volume fraction, and heating water temperature. The FE modeling results were validated by comparing them with previously reported experimental data.

2. Materials and Methods

2.1. Experimental Setup

Caccavelli et al. [26] investigated the thermal performance (both steady-state and dynamic) of a hydronic radiant floor heating system. Their study was used for validation purposes. They constructed a 3000 mm × 3000 mm insulated test chamber with an adjustable ambient temperature. Figure 1 shows the cross-section of the hydronic radiant floor heating system, which comprises a 60 mm thick concrete slab sandwiched between an 8 mm layer of wood at the top and a 60 mm thick insulation panel at the bottom. The heating pipes, embedded 37 mm below the floor surface within the concrete, were consistently spaced at 200 mm intervals. The room and water temperatures were maintained at 19 °C and 36 °C, respectively. Temperature sensors were installed at six distinct locations (A–F), as depicted in Figure 1.

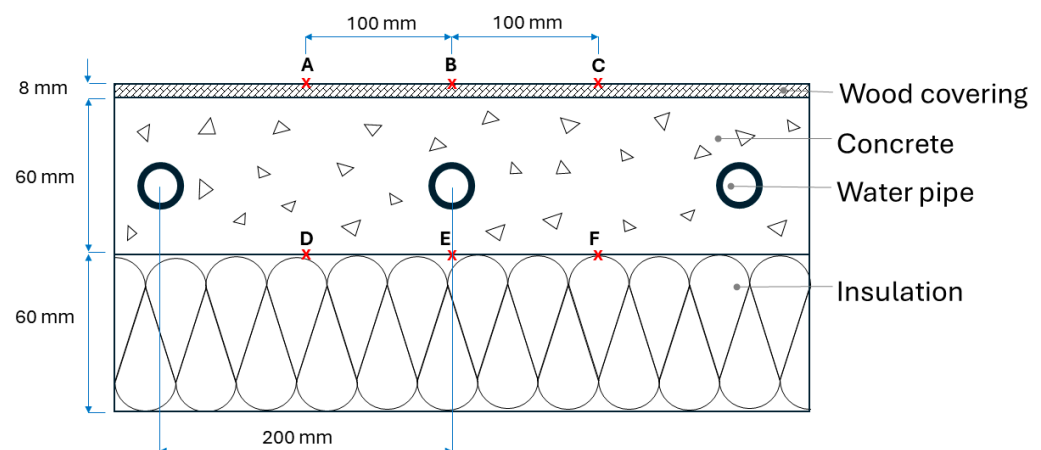


Figure 1. Illustration of the experimental setup showing the location of the temperature sensors.

2.2. FE Modeling

A two-scale FE modeling approach was employed to predict the thermal performance of a hydronic radiant floor heating system integrated with macro-encapsulated PCMs. Initially, the effective thermal conductivity of the concrete mix containing macro-encapsulated PCMs was estimated using a concrete/PCM model. This model yielded two thermal conductivity values for the concrete/PCM mixture, reflecting the phase-dependent thermal conductivities of the PCM. Subsequently, these predicted thermal conductivities were incorporated into the hydronic radiant floor heating system model, and the obtained results were then benchmarked against the experimental data reported by Caccavelli et al. [26].

To simplify the FE modeling of the hydronic radiant floor heating system and accommodate the periodic pattern of the water pipes, a 2-D unit cell containing one heating pipe was constructed, as shown in Figure 2a. Similar unit cells have been employed in previous studies [27,28] to model hydronic radiant floor heating systems. The heating water temperature was assumed to be a consistent 36 °C throughout the pipes. The film coefficient and wood emissivity were considered to be 5.9 W m⁻¹ K⁻² and 0.85, respectively. All layers of the hydronic radiant floor heating system were presumed to be adhered to each other without any air voids or porosity. Macro-encapsulated PCMs were considered to be uniformly distributed in the concrete with a periodic pattern. Consequently, a unit cell for these macro-encapsulated PCMs was designed, featuring spherical macro-encapsulated PCMs encased within a regular concrete cube (Figure 2b,c). The diameters of the PCM and its shell were 8 mm and 10 mm, respectively.

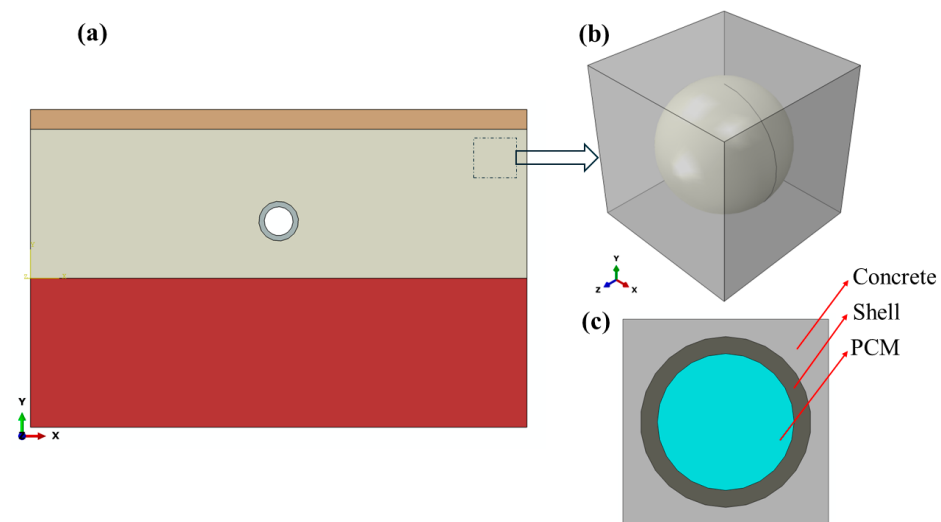


Figure 2. Multiscale FE models of (a) hydronic radiant floor, (b) concrete/PCM, and (c) cross-section of the concrete/PCM model.

The thermal conductivity of the concrete/PCM model was predicted by applying a temperature difference (ΔT) across two opposing faces of the model, while the other faces remained thermally isolated. This temperature gradient caused a heat flow (Q) toward the cooler surface. The equivalent thermal conductivity (k) of the concrete/PCM mixture was then estimated using the Q value in Fourier's law, which was subsequently used for the concrete phase in the hydronic radiant floor [29]:

$$k = -\frac{Q \times L}{A \times \Delta T} \quad (1)$$

where L represents the separation distance between two parallel surfaces across which a temperature gradient is imposed, and A denotes the cross-sectional area of the surface that has either a higher or lower temperature.

The material properties of the hydronic radiant floor and PCM encapsulation are detailed in Table 1. The density and specific heat of the concrete/PCM mixture in the hydronic radiant floor model were determined by applying the rule of mixtures as follows:

$$\rho_{c/pcm} = \rho_c V_c + \rho_s V_s + \rho_{pcm} V_{pcm} \quad (2)$$

$$Cp_{c/pcm} = Cp_c V_c + Cp_s V_s + Cp_{pcm} V_{pcm} \quad (3)$$

Table 1. Material properties of the constituent materials of the hydronic radiant floor.

Material	Density	Specific Heat	Thermal Conductivity	Source
	Kg m ^{−3}	J kg ^{−1} K ^{−1}	W m ^{−1} K ^{−1}	
Concrete	2300	900	1.7	[28]
Wood floor	500	1500	0.14	[28]
Water pipe	1200	1400	0.24	[30]
Insulation	30	1440	0.04	[28]
Polyethylene terephthalate (PET)	1380	1255	0.3	[31]
PCM	1260	1460 (Solid) 1700 (Liquid)	1.09 (Solid) 0.52 (Liquid)	[19]

The variables ρ , C_p , and V represent density, specific heat, and volume fraction, respectively. The subscripts c/pcm , c , s , and pcm denote the concrete/PCM mixture, concrete, shell, and PCM, respectively. The PCM used in these models exhibited a heat of fusion of 220 kJ/kg, with solidus and liquidus temperatures at 27 °C and 29 °C, respectively [19]. Similar to density and specific heat, the latent heat of the concrete/PCM in the hydronic radiant floor model was calculated using the rule of mixtures as follows:

$$H_{c/pcm} = H_{pcm} V_{pcm} \quad (4)$$

where H is the latent heat.

3. Results and Discussion

3.1. Model Validation

The FE modeling data obtained in this study were compared with the steady-state and dynamic thermal behavior of the hydronic radiant floor heating system reported by Caccavelli et al. [26]. Figures 3 and 4 compare the steady-state results at the top of the wood covering layer and the bottom of the concrete floor, respectively. The FE and experimental results matched well. However, the experimental data showed that sensors C and F recorded slightly lower temperatures than sensors A and D, respectively. This discrepancy was attributed to heat losses during water circulation, which were not accounted for in the model due to its simplification. Figure 5 presents a comparison of the FE modeling with the experimental dynamic thermal behavior results at sensor B. The dynamic thermal analysis involved heating the floor for 16 h followed by an 8 h period with the heating turned off. The comparison revealed good agreement in behavior; however, the values were slightly offset. This discrepancy can be attributed to the heat transfer coefficient values, which were fixed in the model.

3.2. Effect of PCM Volume Fraction

The PCM volume fraction significantly affects the thermal properties of the concrete layer, as well as its heat absorption and release capacity. Consequently, we constructed multiple concrete/PCM models with varying volume fractions. Each model contained spherical PCMs encapsulated by PET, maintaining a total diameter of 10 mm, while the volume of the concrete phase was altered. Table 2 presents the volume fraction of each phase for each model, along with specific heat, density, and latent heat values. These values were calculated based on the volume fractions using the rule of mixtures, as per Equations (2)–(4). We predicted the thermal conductivities of the concrete/PCM mixture using the concrete/PCM model. These predicted values were then applied to the hydronic radiant floor model. The outcomes of this application are shown in Figures 6 and 7 for points B and C, respectively.

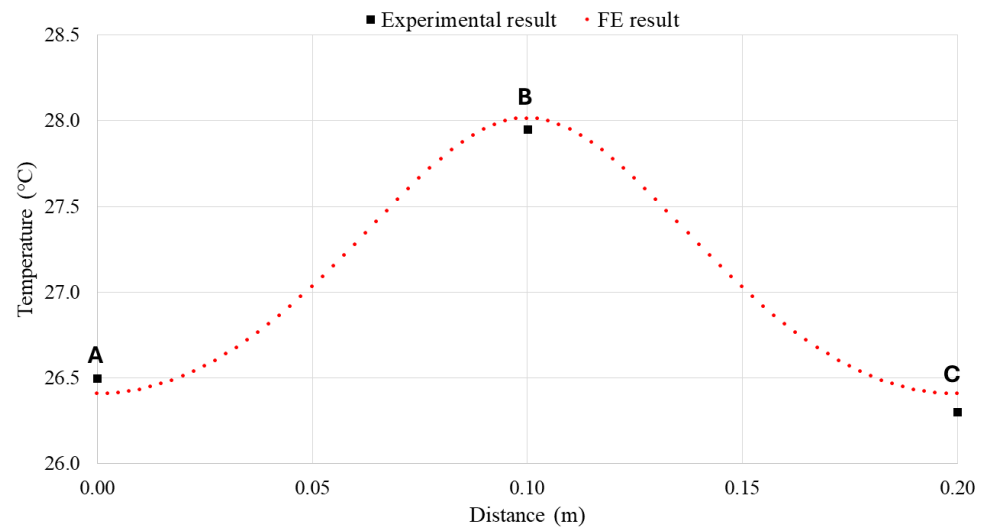


Figure 3. Comparison between experimental and FE steady-state results at the top of the wood covering layer, at points A, B, and C.

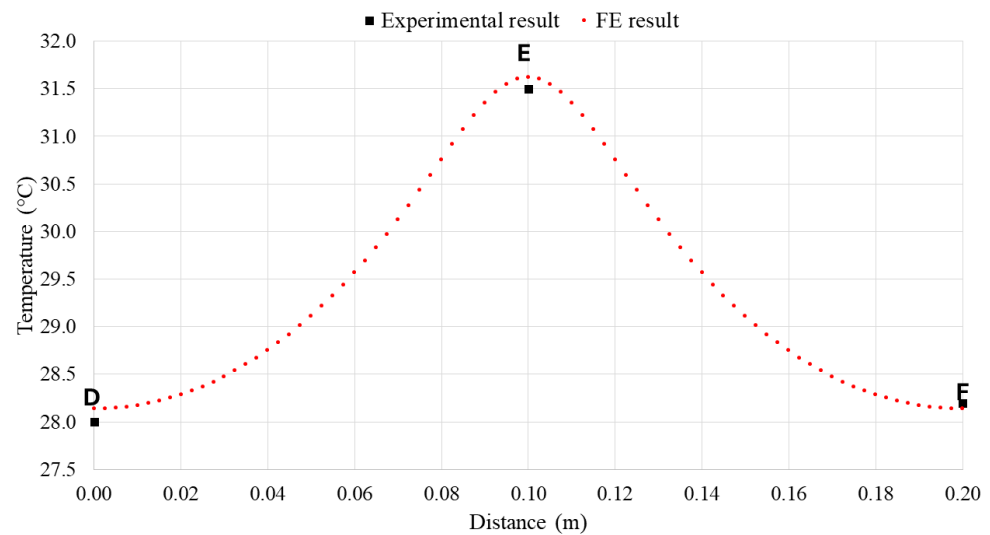


Figure 4. Comparison between experimental and FE steady-state results at the bottom of the concrete layer, at points D, E, and F.

Table 2. Specific heat, density, latent heat, and thermal conductivity of the concrete/PCM mixture at different volume fractions obtained using the rule of mixtures and concrete/PCM model.

Volume Fractions			Specific Heat		Density	Latent Heat	Concrete/PCM Thermal Conductivity (W m ⁻¹ K ⁻¹)	
			(J kg ⁻¹ K ⁻¹)					
Concrete	PCM	Shell	Solid	Liquid	(Kg m ⁻³)	(J kg ⁻¹)	Solid	Liquid
0.5	0.256	0.244	1128.76	1190.2	1809.28	56,320.07	1.066	0.945
0.6	0.2048	0.1952	1083.01	1132.16	1907.42	45,056.05	1.185	1.084
0.7	0.1536	0.1464	1037.26	1074.12	2005.57	33,792.04	1.305	1.227
0.8	0.1024	0.0976	991.5	1016.08	2103.71	22,528.03	1.43	1.375
0.9	0.0512	0.0488	945.75	958.04	2201.86	11,264.01	1.59	1.56
0.95	0.0256	0.0244	922.88	929.02	2250.93	5632.01	1.63	1.615

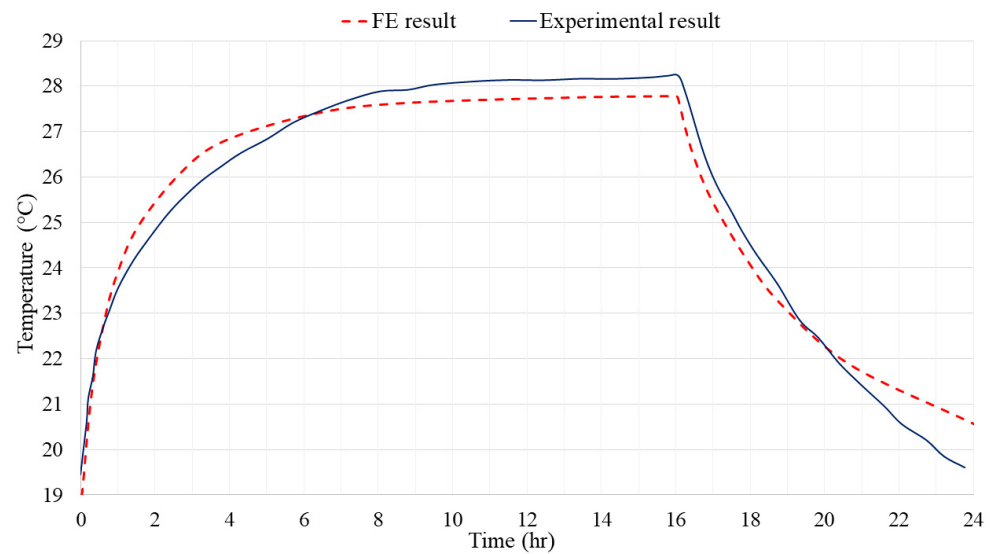


Figure 5. Comparison between experimental and FE dynamic thermal behavior results at point B.

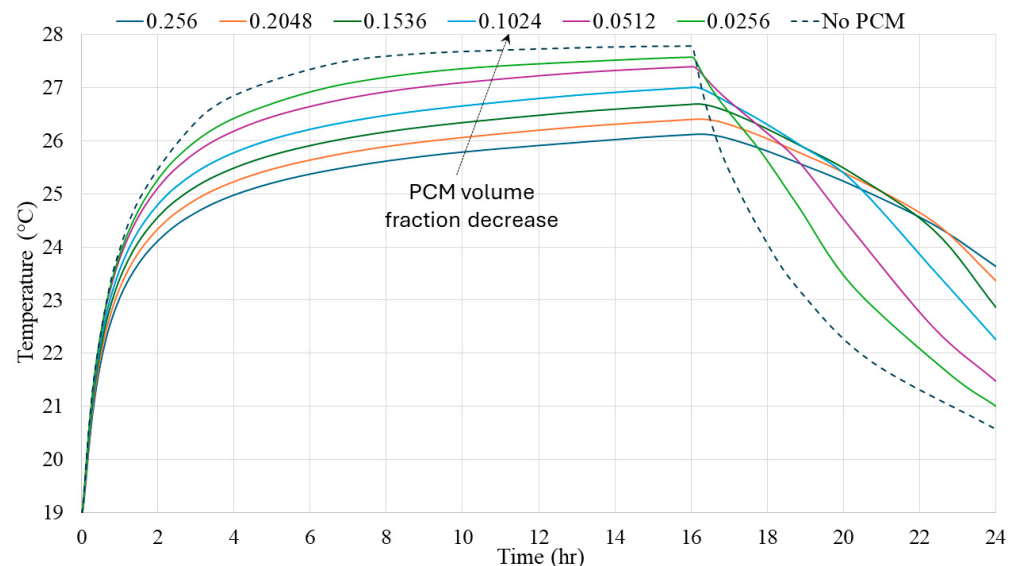


Figure 6. Time–temperature plots at point B of the hydronic radiant floor with various PCM volume fractions.

The temperature difference between heat absorption and release is critical for the hydronic radiant floor integrated with PCMs. Achieving optimal thermal comfort conditions requires a minimal temperature differential during these stages. This difference can be identified as the disparity between the peak temperature (around the 16th hour) and the temperature at the end of the cycle (24th hour), as shown in Figures 6 and 7 for points B and C, respectively. The data indicate that a lower PCM volume fraction results in a greater temperature difference between the peak and the end of the cycle. For example, without PCMs, the temperature at point B dropped by more than 7 °C, while at point C it decreased by approximately 6 °C. In contrast, with a PCM content of 0.256, the temperature difference did not exceed 3 °C and 1 °C at points B and C, respectively. Figure 8 shows the temperature loss per hour at points B and C with various PCM volume fractions after the heating was switched off (post 16 h). The PCM content of 0.256 reduced the temperature loss at points B and C by 66% and 80%, respectively, compared to the hydronic floor without PCMs. Furthermore, as shown in Figures 6 and 7 a lower PCM volume fraction led to higher temperatures on the wood surface; however, the impact was less pronounced than on the temperature difference. For instance, a 0.256 PCM content lowered the maximum

temperature from 27.7 °C to 26.1 °C at point B and from 26 °C to 24.25 °C at point C. Based on the above results, maximizing the PCM content above the heating pipe and decreasing the PCM content as the distance from the heating pipe increases is recommended. This will result in better temperature distribution on the surface when the heating water is on or off and maintain the heat.

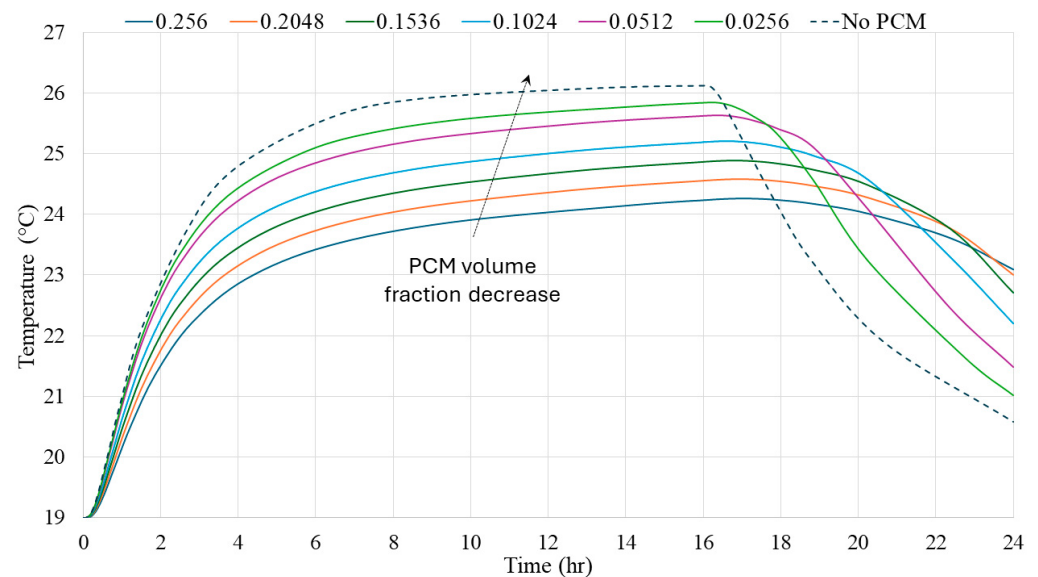


Figure 7. Time–temperature plots at point C of the hydronic radiant floor with various PCM volume fractions.

3.3. Effect of Shell Thermal Conductivity

The selection of shell or capsule material significantly influences the shape, mechanical characteristics, and thermal properties of macro-encapsulated PCMs [32]. Consequently, the shell material in the concrete/PCM model was assigned thermal conductivity values ranging from 0.3 to 15 W m^{−1} K^{−1}. The volume fractions for the concrete, PCM, and shell were 0.7, 0.1536, and 0.1464, respectively. Table 3 presents the predicted thermal conductivities of the concrete/PCM mixture derived from the model. These values were then applied to the hydronic radiant floor model. Figures 9 and 10 show the results at points B and C, respectively.

Table 3. Thermal conductivity of the concrete/PCM mixture obtained from the concrete/PCM model with various shell thermal conductivities.

Thermal Conductivity (W m ^{−1} K ^{−1})		
Shell	Concrete/PCM	
	Solid	Liquid
0.3	1.305	1.227
1	1.485	1.368
3	1.762	1.651
6	2.054	1.968
9	2.275	2.207
12	2.45	2.394
15	2.591	2.546

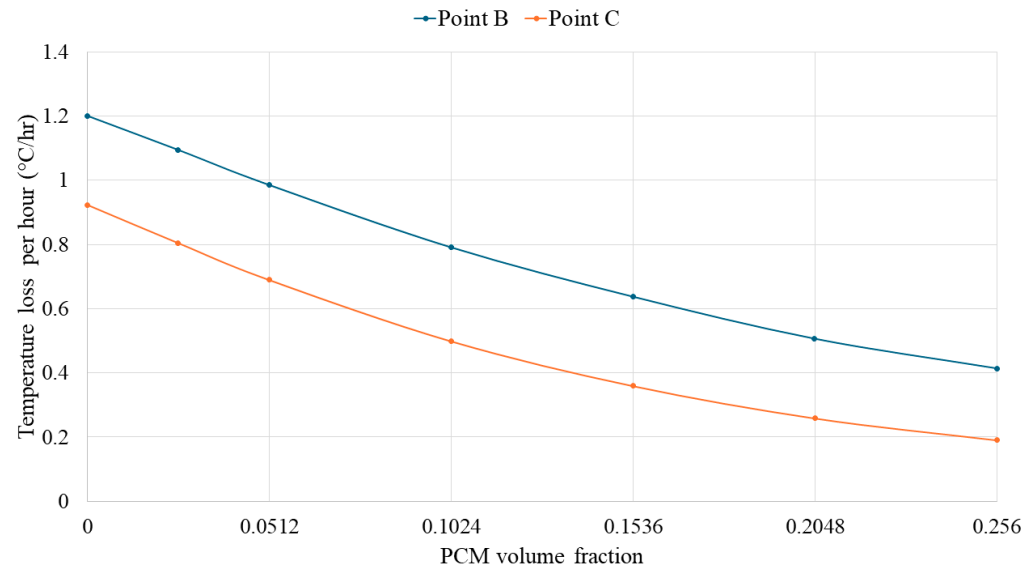


Figure 8. Temperature loss per hour at points B and C of the hydronic radiant floor with various PCM volume fractions.

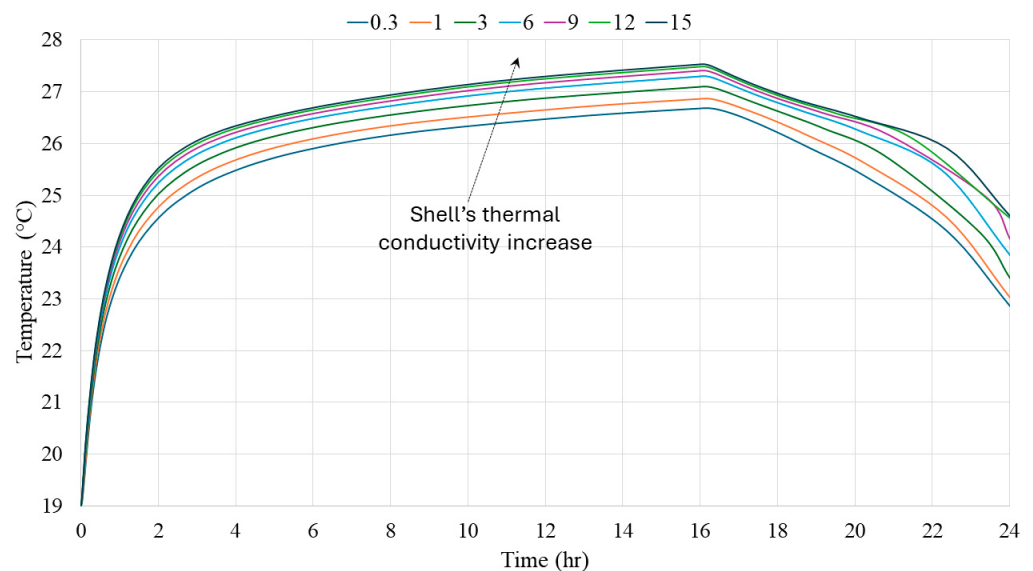


Figure 9. Time–temperature plots at point B of the hydronic radiant floor with different thermal conductivity values of the shell.

Table 3 demonstrates that, although the maximum thermal conductivity of the shell reached $15 W m^{-1} K^{-1}$ (fifty times its initial value of $0.3 W m^{-1} K^{-1}$), the thermal conductivity of the concrete/PCM mixture did not surpass twice its initial values, recorded at 1.305 and $1.227 W m^{-1} K^{-1}$ for the solid and liquid phases, respectively. This limited increase can be attributed to the low volume fraction of the shell material (0.1464) and the low thermal conductivities of the other constituents. Figures 9 and 10 show the impact of the effective thermal conductivity of the concrete/PCM mixture on the dynamic behavior of the hydronic radiant floor model. While enhancing the thermal conductivity of the capsule materials increases the maximum temperature of the floor, the effect is marginal relative to the substantial increase in the thermal conductivity of the shell. Specifically, increasing the thermal conductivity of the shell from 0.3 to $15 W m^{-1} K^{-1}$ resulted in an increase in surface temperature at points B and C by $1^{\circ}C$ and $1.2^{\circ}C$, respectively.

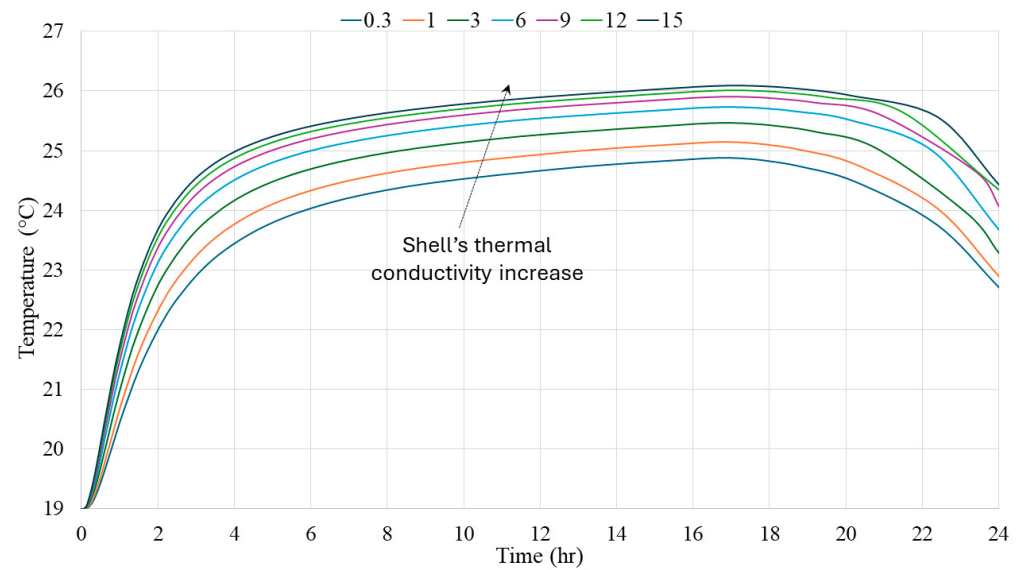


Figure 10. Time–temperature plots at point C of the hydronic radiant floor with different thermal conductivity values of the shell.

3.4. Effect of Macro Capsule Shape

The shape of the macro-encapsulated PCM influences heat transfer through the concrete layer. Consequently, a new concrete/PCM model incorporating various macro capsule shapes was developed. This model features a cubic-shaped macro capsule, as shown in Figure 11b,c. The aspect ratios for these models were set at 1 and 0.33. The volume fractions of the concrete, PCM, and shell were maintained consistently across all three models at 0.5, 0.256, and 0.244, respectively, with the capsule material being PET. Table 4 presents the predicted thermal conductivities for the concrete/PCM mixture derived from the concrete/PCM model. These values were then applied to the hydronic radiant floor model. The results at points B and C are shown in Figures 12 and 13, respectively.

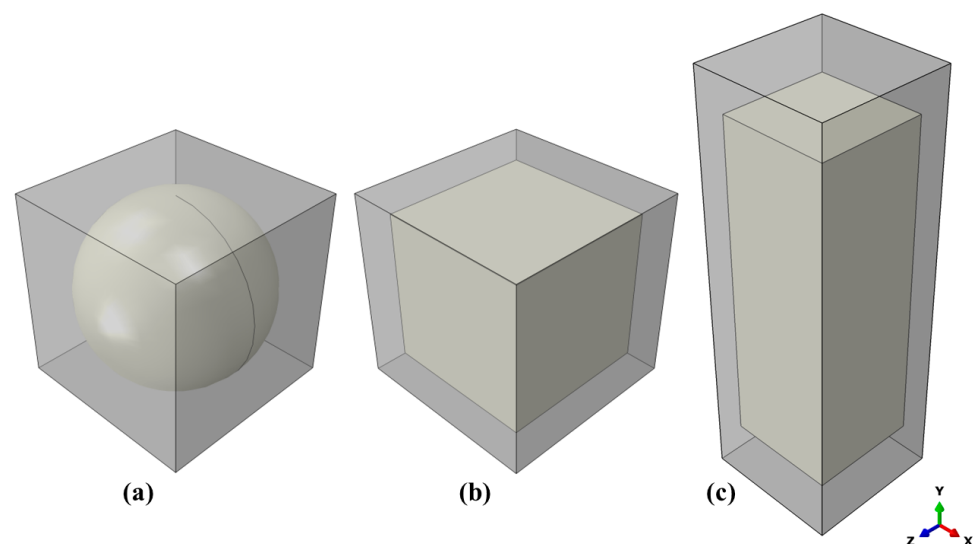


Figure 11. Concrete/PCM model with different shapes: (a) sphere, (b) cube, and (c) cube with an aspect ratio of 0.33.

Table 4. Thermal conductivity of the concrete/PCM mixture obtained from the concrete/PCM model with different shapes.

Shape	Concrete/PCM Thermal Conductivity ($\text{W m}^{-1} \text{K}^{-1}$)	
	Solid	Liquid
Sphere	1.066	0.945
Cube	1.077	0.951
Cube (aspect ratio = 0.33)	1.067 (X&Z)	0.945 (X&Z)
	1.106 (Y)	0.967 (Y)

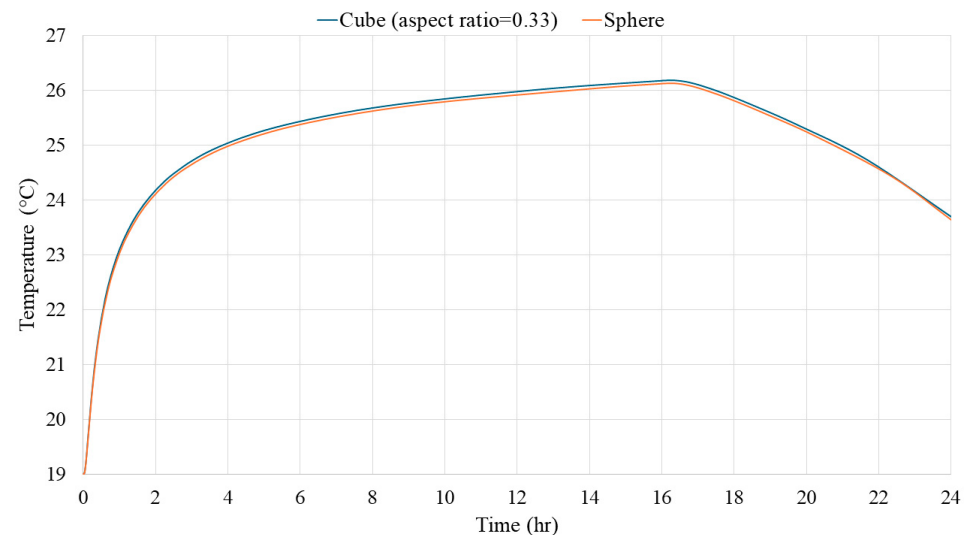
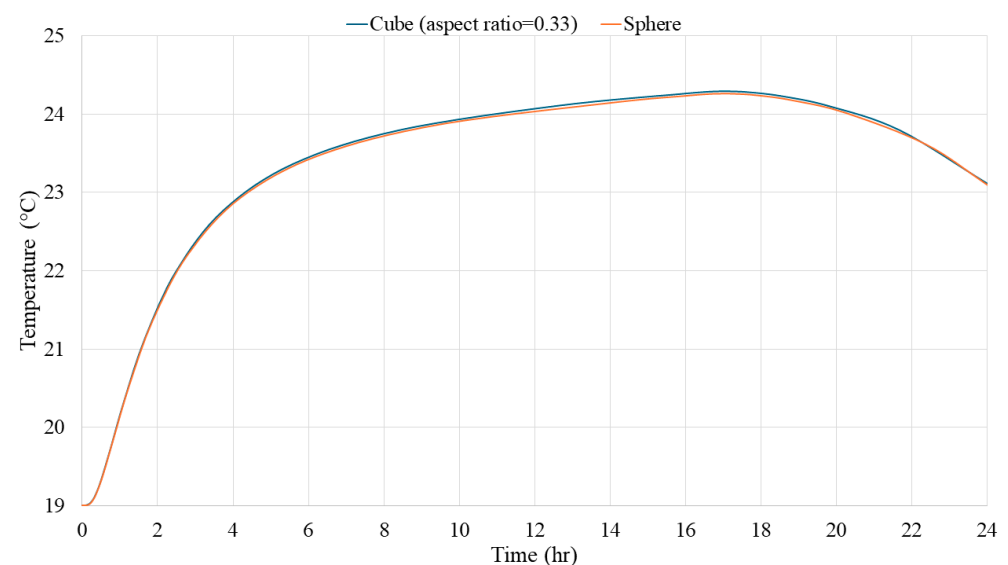
**Figure 12.** Time–temperature plots at point B of the hydronic radiant floor with different shapes of macro-encapsulated PCMs.

Table 4 shows that the shape of the macro-encapsulated PCM had minimal influence on the thermal conductivity of the concrete/PCM phase. However, elongating the macro-encapsulated PCM enhanced the thermal conductivity of the concrete/PCM. Consequently, this slight increase in the dynamic behavior of the hydronic radiant floor model is shown in Figures 12 and 13.

**Figure 13.** Time–temperature plots at point C of the hydronic radiant floor with different shapes of macro-encapsulated PCMs.

3.5. Effect of Water Temperature

The water temperature for heating significantly influences the performance of hydronic radiant floor systems. Consequently, the model was assigned varying water temperatures from 36 to 44 °C. The volume fractions for the concrete, PCM, and shell were set at 0.7, 0.1536, and 0.1464, respectively, with PET as the capsule material. Figures 14 and 15 show the time–temperature profiles at points B and C on the hydronic radiant floor under different water temperatures. These figures indicate that a 2 °C increase in water temperature results in a 0.7 to 0.8 °C increase in floor temperature at point B and a 0.3 to 0.4 °C increase at point C. Figure 14 reveals a sharp decline in surface temperature after the heating was switched off (post 16 h) for water temperatures exceeding 40 °C. The hydronic radiant floor model exhibited optimal behavior at point B with a water temperature of 38 °C, where the surface temperature decreased gradually and consistently during the heat release phase. Thus, selecting a PCM with an appropriate melting point is crucial in the early design phase, considering the anticipated heating water and ambient temperatures. For point C, as shown in Figure 15, all cases were similar; however, higher temperatures resulted in a smaller temperature differential during the release stage.

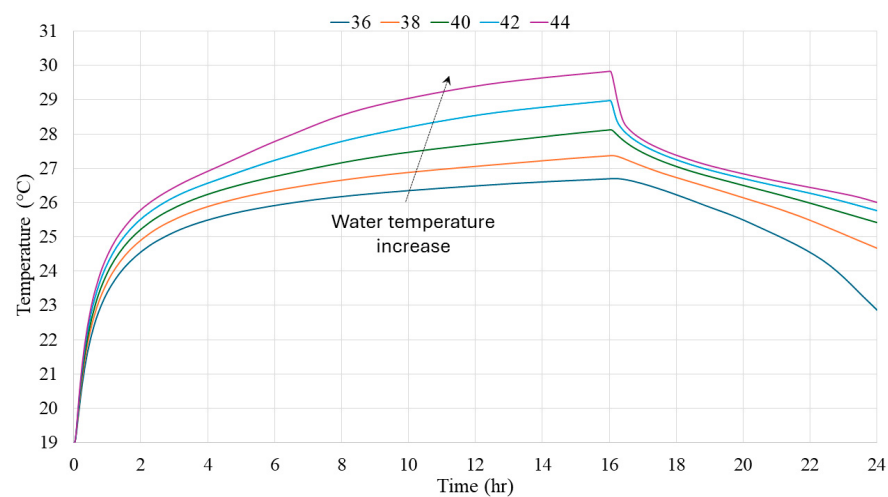


Figure 14. Time–temperature plots at point B of the hydronic radiant floor with different heating water temperatures.

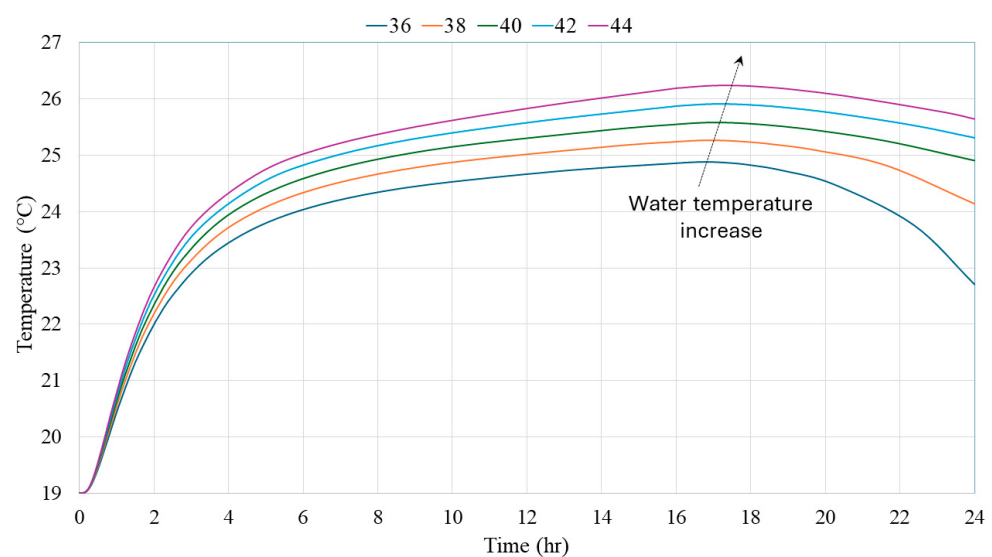


Figure 15. Time–temperature plots at point C of the hydronic radiant floor with different heating water temperatures.

4. Conclusions

This study numerically examined the impact of embedding macro-encapsulated PCMs on the thermal performance of a hydronic radiant floor. It also emphasized the effects of PCM volume fraction, shape, capsule thermal conductivity, and heating water temperature. In summary, the results can be briefly summarized as follows:

1. The implemented multiscale FE model effectively predicted the thermal performance of the hydronic radiant floor heating system under both steady-state and dynamic conditions.
2. Macro-encapsulated PCMs reduce heat flow to the surface, lower the surface temperature during operation, and retain heat when the heating water is turned off. For example, the surface temperature was reduced by 7 °C in the heating floor without PCMs and less than 3 °C in the heating floor integrated with a PCM content of 0.256.
3. Maximizing the PCM content above the heating pipe and decreasing it as the distance from the heating pipe increases is recommended.
4. Selecting a PCM with an appropriate melting point is crucial early in the design stage, taking into account the expected heating water and ambient temperatures to prevent sudden temperature drops after the heating water is turned off.
5. The impact of the macro-encapsulated PCM shape and shell thermal conductivity is minimal. For instance, increasing the thermal conductivity of the shell of the PCM microcapsule fifty times from 0.3 to 15 W m⁻¹ K⁻¹ resulted in an increase in surface temperature by 1.2 °C.
6. Two major limitations of this study could be addressed in future research. First, the study did not consider the effect of the air gap between the layers of the hydronic heating floor. Second, it did not examine different heating pipe layout patterns.

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Data Availability Statement: Data is contained within the article.

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Conflicts of Interest: The author declares no conflicts of interest.

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