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Refining the Integration of Encapsulated Phase Change Materials in Building Envelopes

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ABSTRACT

The demand for cooling of buildings is continuously growing due to global warming contributing to more global CO2 emissions. Escalating resource costs and climate change risks intensify the need for efficient cooling solutions. Phase change materials have been used in building envelopes to reduce the energy consumption. However, these materials are often costly, which creates a barrier for their implementation. Reducing the PCM quantities without compromising their behavior provides a substantial reduction to their overall payback period and increases their feasibility. This study aims to optimize the incorporation of encapsulated PCM in building envelopes by studying the effect of their distribution pattern within the walls. The simulations are done using 2D finite element method. The results indicate that PCM distribution has an important effect on the efficiency of the design and an optimal distribution can allow the reduction of PCM quantities in a wall. In the studied case, the lowest cooling load was found at 14% volumetric percentage of PCM rather than 30% if optimal distribution is used. This consequently have important implications on the need for geometrical optimization when it comes to encapsulated PCM systems.

Keywords: Phase change materials, optimization, spatial impact, cooling/heating, buildings

NONMENCLATURE

Abbreviations	
GWP	Global Warming Potential
kgCO2 eq	Kg carbon dioxide equivalent
PCMs	Phase change materials
$T_{p,c}$	Temperature phase change

1. INTRODUCTION

The escalating global energy demand, primarily fueled by fossil fuels, has led to environmental concerns and an urgent need for sustainable energy sources. The construction sector, responsible for a substantial portion of energy consumption, particularly heating and cooling systems, contributes significantly to global warming and CO2 emissions [1, 2]. To address this, researchers are exploring alternatives like phase change materials (PCMs) to enhance energy efficiency [3, 4]. PCMs, when integrated into building structures, offer passive cooling potential by harnessing latent heat. Conventional cooling techniques are known for high energy consumption and environmental impact [5, 6]. Recently, there has been a growing focus on elevating the effectiveness of PCM due to their potential in improving energy efficiency, sustainability, and address environmental issues [7, 8]. This results in drawing heavier attention from researchers and industries in different fields [9, 10]. However, research gaps exist, in different aspects such as the distribution of PCMs within building structures, integrating additive materials such as metal strands with PCM to increase its thermal conductivity; the addition of a nucleating agent to eliminate super-cooling; and the use of a suitable PCM thickness to prevent incongruous fusion. The positioning of PCMs within walls is crucial for their performance [11], with the optimal position being highly dependent on a variety of factors including climate conditions, wall materials, and wall orientation. Layering strategies have been explored, with varying combinations of PCM and other materials. Despite these advancements, further research is needed to optimize the distribution of PCMs in walls for maximum thermal performance [12]. Although optimizing the heat transfer efficiency of PCM modules has received substantial

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interest in the energy-saving sector [10, 13], and the research has investigated methods of enhancing the performance of PCM such as appropriate implementation [14], material hosting [15], PCM material like composite PCM [16, 5], and machine learning [17], research still lacks investigating the distribution of PCM and its effect on the performance. Thus, in this study, enhancing PCM is investigated based on geometry and distribution.

This study aims to optimize the encapsulation of PCM in building concrete walls, considering different distribution scenarios and their impact on cooling performance, cost, and efficiency [14, 18].

The objectives of this study are to: (i) study the effect of the PCM distribution on the performance of PCM and investigate different patterns with various PCM quantities; and (ii) find how the distribution of PCM is affecting its performance. The novelty of this research lies in two main aspects: studying the relation between the distribution, the percentage, and the performance of the PCM, and showing that higher amount of PCM does not necessarily lead to better performance. A better performance can be reached with lower PCM quantities if the distribution of the PCM capsules is optimized.

2. METHODOLOGY

2.1 Framework

In this study, PCMs are strategically placed in different configurations within a 2D room. Each configuration consists of a matrix with varying numbers of rows and columns containing PCM-filled buckets. The number of columns is systematically reduced from 8 to 4, and within each configuration, the quantity of PCM is adjusted until reaching the optimal percentage. Subsequently, all configurations undergo simulation using the 2D finite element method in COMSOL Multiphysics. This approach allows for a detailed examination of how the distribution of PCM influences its overall performance.

2.2 Mathematical formulation

In the following study, the energy required to cool the enclosure is calculated through the equations below [19]:

$$Q = \dot{m}\, C_p\, \Delta T \qquad \text{Eq 1}$$

Where Q is the energy consumed in kJ, $\dot{m}$ is the mass of air (kg), C_p is the specific heat of the air (kJ/kg.K), it is affected by the phase change material in liquid and solid states presented in Eq 3, and ΔT is the temperature difference in (K), $\dot{m}$ is the mass of air which is calculated as follows:

$$\dot{m} = \rho\, v \qquad \text{Eq 2}$$

The specific heat is dependent on the state of the material whether it is liquid or solid as presented in:

$$C_p = \frac{1}{\rho}\left(\theta_1 \rho_1 C_{p,1} + \theta_2 \rho_2 C_{p,2}\right) + L_{1-2}\,\frac{\partial \propto_m}{\partial T} \qquad \text{Eq 3}$$

ρ and θ are the density and phase fraction which varies from 0 to 1, the indices 1 and 2 presents the liquid or solid state of the material. L is the latent heat of fusion, and $\frac{\partial \propto_m}{\partial T}$ is presented by:

$$\frac{\partial \propto_m}{\partial T} = \frac{1}{2}\,\frac{\theta_2\rho_2 - \theta_1\rho_1}{\theta_2\rho_2 + \theta_1\rho_1} \qquad \text{Eq 4}$$

The thermal conductivity (W/(m.K)) of the material is dependent on the phase change as well and is presented as the following equation:

$$k = \theta_1 k_1 + \theta_2 k_2 \qquad \text{Eq 5}$$

2.3 Computational domain

The model was benchmarked by simulating the DSC experiment of water and comparing the results to the experimental DSC results. A mesh sensitivity was carried out, where a refined mesh was chosen with an error less than 0.5% and relative tolerance less than 0.1%. The study addresses high indoor temperatures caused by exterior wall temperatures ranging from 25 to 40°C. This leads to an interior temperature of 39°C at a 1m distance from the wall, necessitating significant cooling. The energy required for an air conditioner to lower the temperature to 22°C is calculated as 391.68 kJ for an 18 m3 enclosure. The exterior wall's temperature is assumed to be at an average of 30°C.

2.4 System description

The research aims to keep the building interior temperature near the comfort temperature (around 22 oC) by incorporating heptadecane PCM into a conventional concrete wall, enhancing energy efficiency, and reducing cooling-related economic and environmental expenses. Through COMSOL simulations, various designs were tested by progressively adding PCM in specific quantities and distributions. The investigation considered both the thermal transfer impact and cooling efficiency, along with heat conservation. The enclosure dimensions are 1m in height and 2m in width, with 0.1m thick walls on two sides. The integration of PCM involves encapsulating it within buckets arranged in a wall formation—a matrix comprised of PCM-filled buckets with varying rows and columns, as illustrated in Figure 1-a. The initial percentage of PCM is set at 30%, and it undergoes a gradual reduction until reaching the optimal amount necessary to achieve the desired temperature.

This optimization is influenced by the material properties, as depicted in Figure 1-b.

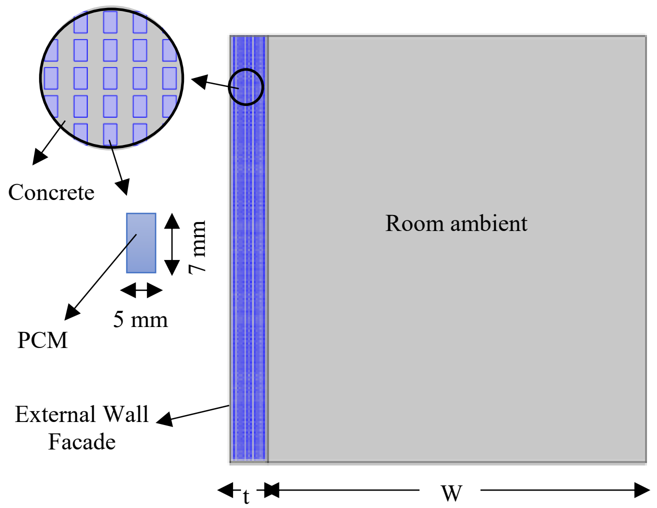

Figure 1-a: The enclosure's design model

Parametric conditions			
Height (H)	1 m	Width (W)	2 m
Wall thickness (t)	0.1 m		
Boundary conditions			
Outside T	30°C	Required T	22°C
Thermophysical properties			
Concrete		Heptadecane	
Density		Latent heat	240kJ/kg
Thermal conductivity	0.9W/(m.K)	$T_{p,c}$	22°C
Heat Capacity	900J/(kg.K)		

Figure 2-b: operating conditions and materials' properties

3. RESULTS AND DISCUSSIONS

Based on the results of interior temperature and cooling load calculations, it was noticed that higher amount of PCM is not necessarily responsible for better performance, where at low quantity of PCM the desired comfort temperature (22 oC) could be attained. In the following section, the optimum case of each model is displayed. In each model the amount of PCM integrated was set at specific percentage, then it was decreased gradually to reach the required temperature. The required temperature was reached at different percentages affected by the mode design or the distribution of the PCM. A distribution factor (dy/dx) is introduced to describe the special distribution of PCM in the x (horizontal) and y (direction). dx represents the distance between the capsules in the x direction and dy represents the distance between the capsules in the x direction. When the capsules are designed as parallel plates, the dy/dx factor would be zero.

This model started with 8 columns, where the required temperature was attained at 23.8% of PCM. Then, the number of columns was reduced gradually to find the effect of variation of the percentage and the distribution of PCM. Results showed that the required temperature was fulfilled at 14% of PCM with 4 columns. Figure 2 indicates that the temperature inside the enclosure reaches 21.95°C with 14% of PCM rather than 23.8% at 8 columns. Besides, it was noticed that a compacted PCM column with closer buckets in the y direction improves efficiency, which is presented by the distribution factor (dy/dx). This factor shows the distance between the rows to the distance between the columns. It is noted that as this ratio is decreased the performance is increased. In other words, for the same quantity, increasing the number of buckets vertically while reducing to number of columns to 3 will cause the buckets to form plates.

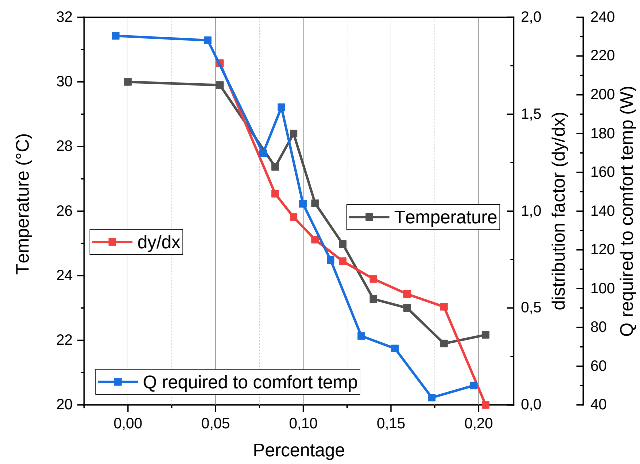

Figure 3: Inside temperature variation with decreasing the percentage of PCM for 4 columns.

4. CONCLUSION

In this study, a model of an enclosure, with concrete walls containing encapsulated PCM (heptadecane) was simulated. The variation of the amount of PCM was studied through different distribution to find the effect of the distribution on the performance of PCM.

The incorporation of heptadecane in the concrete wall decreased the cooling loads needed to maintain comfort temperature drastically. The following conclusions were drawn:

PCM incorporation decreased the reliance on polluting electricity-generating methods and refrigerants and lessened the price of this facility.

At 4 columns of PCM the optimum percentage reached at 14%, however at 8 columns the optimum percentage was reached at 23.8%. Thus, the performance of PCM hinges on the distribution rather than quantity, where optimum performance was reached at lower amount of PCM in specific distribution.

Reducing the distribution factor to a non-zero specific value enhances the performance of PCM. Thus, a study on PCM distributed in plates is recommended.

It is recommended to study the environmental and economic effects of this optimization as it is noticed that the optimum performance was reached at 14%, almost half the amount of PCM for the first configuration (8 columns).

DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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