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Analysis of Phase Change Material in Room Wall for Thermal Regulation: A Computational Fluid Dynamics Approach

Analiza materialului cu schimbare de fază în peretele unei camere pentru reglarea termică: O abordare prin CFD

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Abstract. *The integration of phase change materials (PCMs) into building structures has become a focal point for researchers aiming to enhance thermal comfort and energy efficiency in buildings. This comprehensive article delves into the analysis of PCMs embedded in room walls, emphasizing their role in thermal regulation and the innovative application of computational fluid dynamics (CFD) in evaluating their performance.*

Keywords: Phase Change Materials (PCMs), Thermal Regulation, Sustainable Building Design, Temperature Stabilization, Energy Conservation

1. Introduction

Phase Change Materials (PCMs) are innovative substances that play a pivotal role in energy storage and thermal management. By undergoing phase transitions, typically from solid to liquid or vice versa, these materials can absorb or release significant amounts of energy at predefined, consistent temperatures. This characteristic makes PCMs exceptionally effective in applications where temperature regulation and thermal energy storage are critical.[1]

One of the most compelling attributes of PCMs is their ability to undergo phase transitions at specific, predetermined temperatures. During the melting process, a PCM

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can absorb a substantial amount of latent heat without a significant increase in temperature. Such properties are invaluable in diverse applications, from medical heating pads that deliver controlled warmth to innovative cooling technologies for telecommunications infrastructure and even in advanced textiles designed for thermal comfort in bedding and clothing. [2]

The focus of this project is a computational investigation into the incorporation of PCMs within the structural fabric of buildings, specifically within a room's wall for enhanced thermal regulation. The model considers a square-shaped room, where one of the walls comprises a three-layered composite structure: Brick on the exterior, a layer of Trimethylolethane/water PCM blend, and Concrete on the interior.

The external brick layer is subjected to a constant heat flux of 100 W/m², simulating solar radiation or external thermal conditions. The selection of materials—Brick, Trimethylolethane/water PCM, and Concrete—is critical. Each has been chosen for its specific thermal properties, particularly their low thermal conductivity, which is essential for attenuating the rate of heat transfer and thus stabilizing the internal temperature. [3]

To analyze this system, the study employs a three-dimensional (3D) computational domain replicating a square room with dimensions of 3 meters per side, where each wall layer is uniformly 10 cm thick. The geometry for this simulation is meticulously crafted using Design Modeler software, establishing a precise framework for subsequent analysis. Ansys Meshing software facilitates the generation of a structured mesh grid across the domain, comprising 193,500 elements, ensuring detailed and accurate simulation results. [4]

This project aims to illuminate the potential of PCM-enhanced walls in moderating indoor temperatures, ultimately contributing to the fields of energy efficiency and sustainable building design. By harnessing the thermal inertia provided by PCMs, the study anticipates demonstrating a significant moderation of indoor temperature variations, offering a pathway to more energy-efficient and comfortable living and working environments. [5]

2. Material and method

Simulation Model

The core of our simulation hinges on the Solidification and Melting model, a sophisticated computational tool designed to accurately represent the phase change processes within the Phase Change Material (PCM). This model is adept at simulating the intricate energy exchange that occurs during the transition between solid and liquid states, providing a realistic depiction of PCM behavior within the wall structure. [Fig. 1]

Computational Approach

For the computational fluid dynamics (CFD) analysis, we employed a pressure-based solver, chosen for its effectiveness in handling incompressible fluid scenarios, which aligns well with the characteristics of the PCM in its liquid phase. The pressure-based solver is renowned for its robustness and accuracy in simulations where the fluid density remains relatively constant, which is pertinent to our study as we examine the thermal dynamics within the PCM-enhanced wall. [Fig. 1]

Time-dependent Analysis

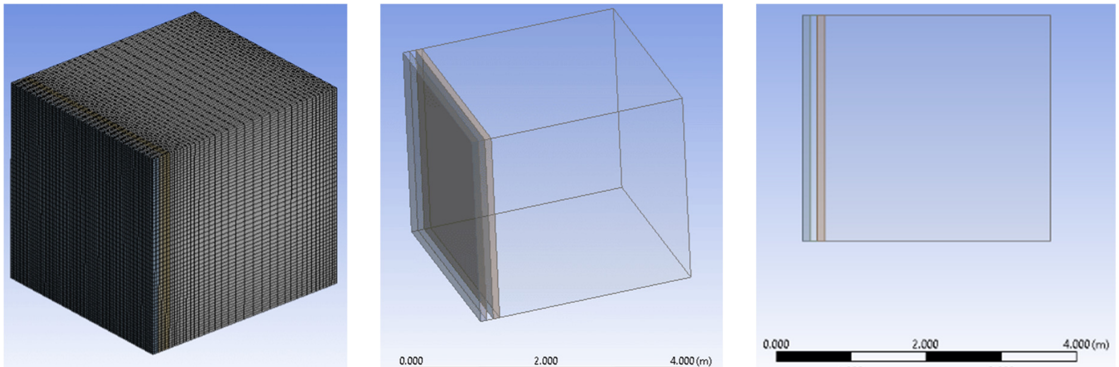
Understanding that the thermal interactions within the wall are inherently time-dependent, our simulation was conducted in a Transient mode. This approach allows us to capture the dynamic nature of the heat transfer and phase change processes over time, offering a detailed temporal resolution of the PCM's thermal response to external and internal temperature variations. [Fig. 1]

Gravitational Effects

In the context of this simulation, the gravitational forces have been deemed negligible. This assumption is justified by focusing on the thermal interactions driven primarily by heat conduction and phase change phenomena rather than convective flows that would be significantly influenced by gravity.

Analytical Environment

The simulation environment is meticulously configured to replicate the operational conditions to which the PCM wall would be subjected. The transient nature of the simulation demands a time-stepped approach, meticulously cataloging the evolution of temperature distribution and phase change progression within the PCM and adjacent materials. [Fig. 1]



a) b) c)

Fig. 1. a) Mesh, b) Geometry, c) Layer of PCM

3. Results

Interpreting Simulation Data Visualizations

The two-dimensional visualizations derived from our simulation offer an in-depth view of the thermal and fluid dynamics occurring within the wall structure, providing a solid foundation for our analysis. The detailed contours and vector fields that illustrate variables such as water pressure, temperature, turbulence kinetic energy, and fluid velocity allow us to comprehend the nuanced interactions between the wall components and the indoor environment. These visualizations are not merely graphical outputs; they are windows into the complex thermal behavior of the system, enabling us to correlate specific design choices with their thermal outcomes. [Fig. 2]

Analyzing PCM Performance

The finding that the Trimethylolethane/water PCM blend requires approximately six days to transition fully from solid to liquid phase is significant. This prolonged phase change duration is indicative of the material's substantial thermal storage capacity, a feature that is essential for its role in thermal regulation. Such a capability allows the PCM to act as a thermal buffer, absorbing heat when available and releasing it gradually, which is critical for reducing thermal shock and enhancing comfort levels within the building. [Fig. 2]

Understanding Temperature Dynamics

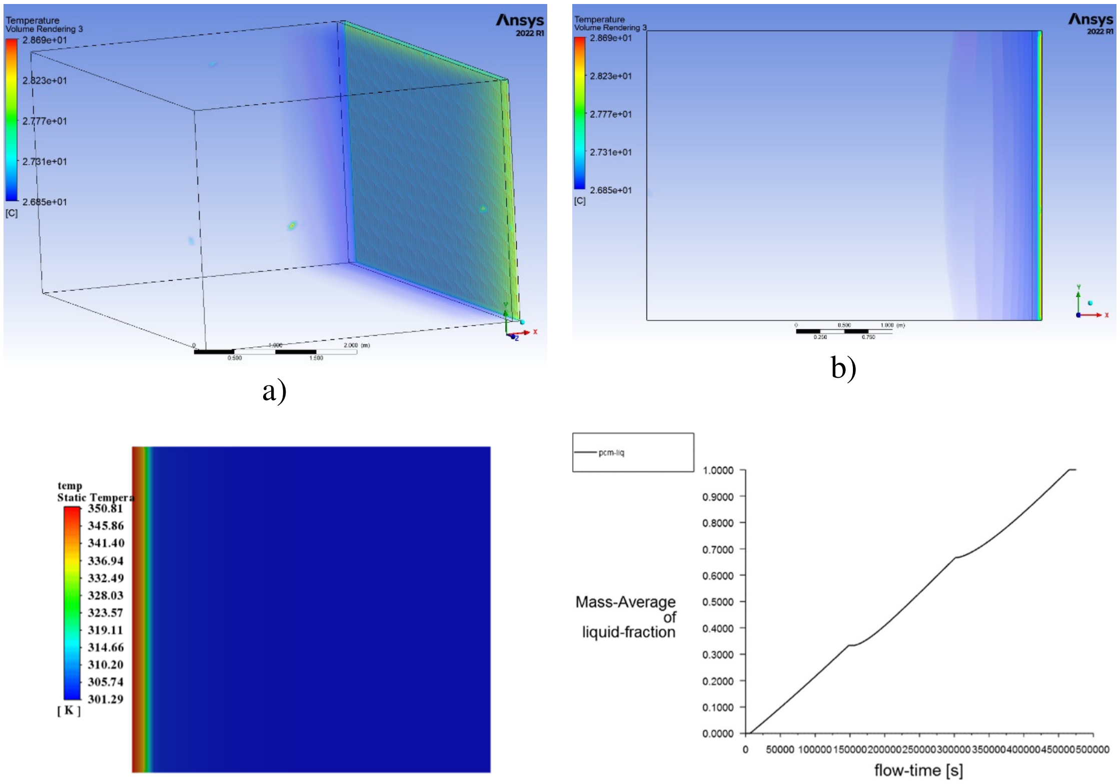
The gradual increase in interior temperature, despite external heat flux, underscores the effectiveness of the wall's multilayer composition in thermal resistance. The inherent low thermal conductivities of Brick, PCM, and Concrete are pivotal in this respect, minimizing heat ingress and stabilizing indoor temperatures. This aspect is particularly noteworthy because it suggests that the building's dependency on external heating or cooling can be substantially reduced, which is a direct indicator of improved energy efficiency. [Fig. 2]

Energy Storage and Strategic Release

The PCM's function as an energy reservoir is a cornerstone of our discussion. This ability to cyclically absorb and release energy equips the building with a form of passive temperature regulation, minimizing the need for active thermal control systems. In essence, the PCM wall acts autonomously, responding to thermal stimuli with minimal external intervention. This characteristic not only demonstrates the PCM's utility in energy conservation but also exemplifies a move towards more autonomous building thermal management systems. [Fig. 2]

Broader Implications for Energy Efficiency

The broader implications of our findings for building energy efficiency are profound. By integrating PCMs into building envelopes, we can potentially transform the way buildings interact with their thermal environment. The decrease in HVAC system dependency not only lowers energy consumption but also contributes to reducing peak load demands on energy infrastructure, which is vital for the sustainability of urban energy systems. Moreover, the implications extend beyond energy savings, affecting aspects such as building design, occupant comfort, and even architectural aesthetics.



a) b)

c) d)

Fig. 2. a), b), c), d) Temperature contours and Mass-Average of Liquid-fraction

4. Discussion

The computational fluid dynamics (CFD) simulation offered a thorough investigation into the role of Phase Change Material (PCM) in enhancing building wall efficiency, focusing on how this material influences thermal regulation. Utilizing two-dimensional visualizations, the study illustrated the variations in water pressure, temperature, turbulence kinetic energy, and velocity, providing crucial insights into the thermal interactions facilitated by PCM integration within the wall. The simulation's significant revelation was the temporal aspect of the PCM's response to thermal inputs, showcasing that the Trimethylolethane/water blend needed around six days to achieve a complete phase transition from solid to liquid. This transition underscores the PCM's ability to store and later release thermal energy, thus stabilizing internal temperatures over extended periods and diminishing the impacts of external temperature changes.

The analysis spotlighted PCM's efficiency during high heat intake periods, demonstrating its capacity to evenly absorb and release heat, ensuring stable and comfortable indoor temperatures without constant mechanical intervention. This feature is particularly advantageous for maintaining uniform indoor climates and reducing energy dependency. The simulation also highlighted how the integration of low-conductive materials like Brick, PCM, and Concrete contributes to the building's thermal inertia, enhancing the insulation effect and preventing rapid temperature shifts.

By interweaving PCM into the building's fabric, the simulation validated a progressive strategy in architectural design, emphasizing material innovation combined with sophisticated simulation methodologies to confirm PCM's real-world applicability. This integration not only acts as a safeguard against thermal extremes but also fosters energy efficiency, offering dual benefits of improved indoor comfort and sustainability. The findings advocate for PCM's broader adoption in construction, heralding a step forward in achieving more energy-efficient and environmentally responsive building designs.

5. Conclusion

This study underscores the detailed simulation results furnish us with a deeper understanding of the practical applications and benefits of incorporating PCMs in building structures. They validate that PCMs can act as a key technological enabler for energy-efficient building design, offering a proactive solution to energy storage and thermal regulation challenges in modern construction practices.

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