Innovative TES Design for Building Energy Management: Computational Investigation of RT-42 and RT-35 PCM Solidification Dynamics

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Abstract

This study proposes an innovative approach for enhancing building energy efficiency by improving the efficiency of a chilled water-based cooling system using a thermal energy storage (TES) unit. The Chiller's refrigerant is bypassed before entering the condenser through TES, which cools down and melts the PCM during the daytime. The excessive chilled water is passed through a phase change material (PCM) base TES unit, which stores the cold energy. That cold energy can be used for peak shaving and energy saving during the day. This study investigates numerically the solidification process of PCM RT-42 and RT-35, filled in a cylindrical TES system containing helical pipes for heat transfer fluid (HTF). As part of a larger perspective aimed at enhancing building energy efficiency, this research milestone focuses on the thermal behaviour and performance of the TES unit during the charging process. Numerical simulations were conducted using ANSYS Fluent to model the solidification process. The simulations analysed heat transfer rates, temperature distribution, and the progression of the solid-liquid interface within the storage unit. The solidification of two PCMs has been studied at 10m/s. The framework for the future of the experimental setup has been demonstrated to involve supplying chilled water from the chiller to a test room equipped with an FCU, where the room temperature is to be studied under varying chilled water flow rates. Crucially, the excessive chilled water flow is diverted and utilized to solidify a PCM in the TES unit. The cold energy will be used for cooling of refrigerant and to cool the return water from the building.

Keywords: Energy efficiency, Thermal Energy Storage, Phase Change Material (PCM), PCM Solidification.

1. Introduction

Buildings account for significant global energy consumption and greenhouse gas emissions due to space cooling and heating requirements [1], [2]. Enhancing building energy efficiency through innovative cooling strategies and optimal utilization of available thermal energy resources is crucial for reducing environmental impact and achieving sustainability goals [3], [4]. TES systems, particularly those utilizing PCM, have gained considerable attention as a promising approach to improving energy efficiency and thermal management in buildings [5], [6].

TES systems have gained significant attention in recent years due to their potential to improve energy efficiency, reduce greenhouse gas emissions, and facilitate the integration of renewable energy sources. TES systems store thermal energy during periods of low or abundant supply and release it when needed, thereby decoupling energy supply and demand [7]. This literature review explores the various types of TES systems, their applications, and recent advancements in the field. TES systems can be classified into three main categories: sensible heat storage, latent heat storage, and thermochemical storage [8]. Sensible heat storage systems store energy by increasing the temperature of a storage medium, such as water, rock, or molten salts [9]. These systems are simple, cost-effective, and widely used in domestic hot water systems and space heating. However, they have relatively low energy storage densities and require large storage volumes.

Latent heat storage systems utilize PCM to store energy during phase transitions, typically from solid to liquid [10]. PCMs offer higher energy storage densities than sensible heat storage materials and maintain a nearly constant temperature during the phase change process [11]. Common PCMs include paraffin, salt hydrates, and fatty acids [12]. Latent heat storage systems have been applied in building energy management, solar thermal power plants, and waste heat recovery [10]. TES systems facilitate the storage and release of thermal energy, enabling the decoupling of energy supply and demand [13]. Among TES technologies, latent heat storage using PCMs has emerged as an attractive solution due to their high energy storage density and ability to store and release energy at a nearly constant temperature [14], [15]. PCMs undergo phase transitions (e.g., solid-liquid or solid-solid) within a specific temperature range, absorbing or releasing latent heat during the phase change process [16], [17].

The integration of TES systems with building cooling systems, such as chillers and fan coil units (FCUs), has been explored to enhance energy efficiency and thermal management [18], [19]. By storing thermal energy during off-peak periods or when excess cooling capacity is available, TES systems can shift cooling loads and reduce peak energy demand, leading to potential cost savings and improved system performance [20], [21]. Several studies have investigated integrating PCM-based TES systems with chillers and FCUs. Rismanchi et al. [22] developed a simulation model to evaluate the potential energy savings and peak load-shifting capabilities of a chiller-TES system for office buildings. Osterman et al. [23] conducted experimental and numerical studies on integrating a PCM-based TES unit with an FCU, exploring the potential for improved cooling performance and energy efficiency.

Computational fluid dynamics (CFD) simulations have been widely employed to model and analyze the thermal behaviour of TES systems, particularly those involving PCMs [24]. CFD simulations can provide valuable insights into the heat transfer mechanisms, phase change dynamics, and thermal performance of TES units, enabling optimization and design refinement [25].

While previous studies have explored the integration of TES systems with building cooling systems, there remains a need for comprehensive investigations focused on optimizing the chiller system with building integration to enhance performance and energy efficiency. Specifically, the simultaneous integration of TES units with chiller systems and FCUs presents an opportunity to explore synergistic effects and potential energy savings. The proposed research presents a numerical investigation of an innovative approach to integrating a PCM-based TES unit with a chiller system. This study provides a comprehensive numerical analysis using ANSYS/Fluent on the solidification of PCM RT-42 and RT-35 by passing the excessive or nigh-time chilled water through TES. The findings of this research provide valuable insights and guidelines for designing and implementing energy-efficient cooling strategies in buildings.

2. EXPERIMENTAL SETUP FRAMEWORK

The proposed system integrates a chiller, an FCU, and a TES unit to enhance building cooling efficiency. In this setup, the Chiller's refrigerant is bypassed before entering the condenser through TES, which cools down and melts the PCM in the daytime. The chiller produces chilled water for the FCU, which cools the test room. Excess chilled water is diverted to the TES unit, solidifying a PCM and storing cold energy. This configuration aims to optimize cooling capacity by utilizing excess chilled water and exploring potential temperature drops in the refrigerant stream. While the experimental phase is yet to be conducted, this integrated system design promises to improve overall energy efficiency in building cooling applications by leveraging TES for peak load management and energy conservation. Figure 1 shows the demonstration of the experimental framework.

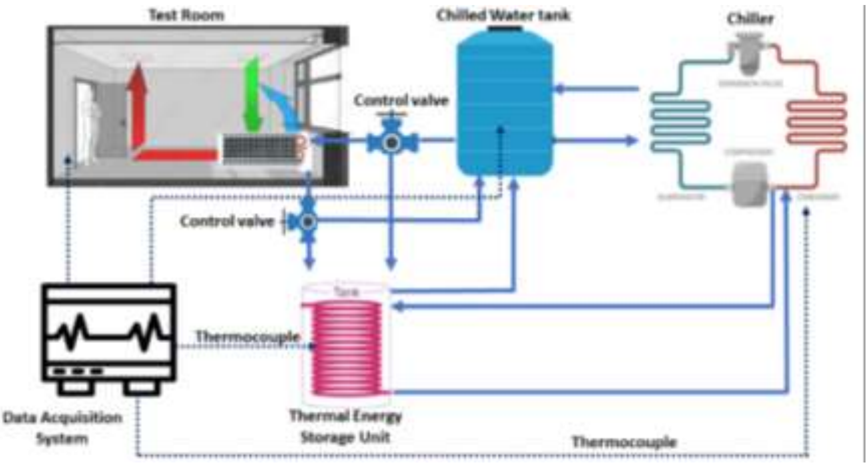

Fig. 1 Experimental demonstration of chilled water cycles from the chiller to building and TES Integration

The experimental setup consists of several interconnected components designed to study thermal energy storage and control systems. The primary elements of this framework include:

- Test Room: A controlled environment where temperature variations and airflow can be monitored and regulated.

- Chilled Water Tank: A reservoir for storing cooled water, which acts as a thermal buffer in the system.

- Chiller: A device responsible for cooling the water in the chilled water tank.
- Thermal Energy Storage Unit: A component designed to store thermal energy using phase change materials.
- Control Valves: Two control valves are incorporated into the system to regulate chilled water flow between different components.
- Data Acquisition System: An electronic system for collecting and recording data from various sensors throughout the experimental setup.
- Thermocouple: Temperature sensors placed at strategic points in the system to measure and monitor thermal conditions.

The experimental framework comprises a closed-loop system where chilled water circulates among key components. A chiller cools water in a chilled water tank, which can be directed to either a test room for direct cooling or excessive chilled water at day or night time, considering cooling load requirements, and can be sent to the thermal energy storage unit to store cold energy using control valves. This configuration allows for precise regulation of cooling distribution and enables the study of various thermal management strategies. The test room, equipped with an FCU for chilled water circulation and thermocouples, facilitates the observation of temperature changes and thermal dynamics. Thermocouples placed throughout the system feed data to an acquisition system, enabling real-time monitoring and analysis of thermal behavior. This integrated setup provides a comprehensive platform for investigating energy efficiency, thermal storage capabilities, and advanced strategies in building cooling applications, offering insights into optimizing thermal management in various conditions.

A. Material Selection

Material selection is important in heat transfer and latent heat storage [26] - [28]. In the next phase of the research by passed refrigerant will pass through TES at a high temperature of 65°C to 70°C, while in this study, solidification of PCM is under consideration. Hence, the RT-42 and RT-35 have been chosen to maintain an appropriate temperature gradient for melting and solidification. This configuration and PCM selection give freedom from the ambient conditions as a free cooling concept is highly dependent on ambient conditions for the solidification of PCM, and the nighttime temperature usually does not drop enough to solidify PCM. The thermophysical properties of RT-42 and RT-35 used in numerical modelling are listed in Table 1.

TABLE 1 THERMOPHYSICAL PROPERTIES OF PCMS

Properties	RT-42	RT-35
-Density-(kg/L)	1.6	1.56
-Melting Point-(°C)	38-43	32-35
-Specific Heat Capacity-(kJ/kg·K)	2	2
-Latent Heat-(kJ/kg)	246	243
-Heat Conductivity-(W/m·K)	0.2	0.2

3. NUMERICAL MODELLING

Using the finite-volume approach, a three-dimensional heat transfer model has been created for a cylindrical TES system using ANSYS/fluent. The system has a diameter of 10 cm and a height of 12 cm, featuring two helical pipes. The outer helical pipe has a circular diameter of 8 cm. In comparison, the inner helical pipe has a circular diameter of 4 cm. Both pipes have an HTF diameter of 1.27 cm and a wall thickness of 0.039 cm. Water has been used as an HTF for the solidification cycle. Copper has been used as the material of pipes with the thickness of the design has been created. This model focuses on the solidification process of RT-42 and RT-35. PCMs have been treated as an incompressible fluid inside the computational domain during the solidification process. Figure 2 shows the model of the TES system.

Fig. 2 TES system model

The differential equation governs the transient heat transfer in two dimensions (1) [25], [29]. A heat flux (q) which represents the incident irradiance, is applied as a boundary condition. In this context, which represents the incident irradiance, it is applied as a boundary condition. In this context ρ is the density c is the specific heat capacity k is the thermal conductivity, T is the temperature, t is time and x_i, and x_j are unit vectors. Equation. Heat losses due to convection and radiation are considered at the boundary, as described by Equations (2) and (3). In these equations Z_c and Z_r represent the convective and radiative heat losses h_c is the convective heat transfer coefficient A is the area, ε is emissivity, σ is the Stefan-Boltzman constant, T_{amb} is ambient temperature, and T_∞ is the sky temperature. By incorporating these boundary heat losses, the unified governing equation for heat transfer is derived, yielding Equation (4). To derive the weak formulation, the test function δT is multiplied by the governing equation and integrated over the domain, leading to Equation (5). Through the application of Green-Gauss and the divergence theorem, the weak formulation is further simplified, as shown in part 2 of Equation (6), resulting in Equation (8). The weak formulation preserves the energy balance for two-dimensional transient heat diffusion, expressed in Equation (7), where $\dot{T}$ is the time derivative of the temperature, and $\hat{q}$ is the irradiance or boundary flux matrix, and M, K, H and R are the mass, conductivity, convection, and radiation matrices, respectively. The temporal discretization of the domain is executed using the Crank-Nicholson method. To simulate heat storage during phase changes, the effective heat capacity method is applied, as depicted in Equation (8).

$$\rho c \frac{\partial T}{\partial t} - \left[\frac{\partial}{\partial x_i} \left(k_{ij} \frac{\partial T}{\partial x_j} \right) \right] = 0 \tag{1}$$

$$Z_c = h_c A(T - T_{amb}) \tag{2}$$

$$Z_r = \sigma \varepsilon A(T^4 - T_\infty^4) \tag{3}$$

$$\rho c \frac{\partial T}{\partial t} - \left[\frac{\partial}{\partial x_i} \left(k_{ij} \frac{\partial T}{\partial x_j} \right) \right] + Z_c + Z_r = 0 \tag{4}$$

$$\underbrace{\int_\Omega \delta T \cdot \rho c \frac{\partial T}{\partial t} \partial \Omega}_{1} - \underbrace{\int_\Omega \delta T \cdot \left[\frac{\partial}{\partial X_i} \left(k_{ij} \frac{\partial T}{\partial X_j} \right) \right] \partial \Omega}_{2} + \underbrace{\int_{\Gamma_\sigma} \delta T \cdot (z_c + z_r) \partial A}_{3} = 0 \tag{5}$$

$$\underbrace{\int_\Omega \delta T \cdot \rho c \frac{\partial T}{\partial t} \partial \Omega}_{1} + \underbrace{\int_\Omega \left[k_{11} \frac{\partial \delta T}{\partial X_1} \left(\frac{\partial T}{\partial X_1} \right) + k_{22} \frac{\partial \delta T}{\partial X_2} \left(\frac{\partial T}{\partial X_2} \right) \right]}_{2} + \underbrace{\int_{\Gamma} \delta T \cdot (z_c + z_r) \partial A}_{3} = 0 \tag{6}$$

$$M\dot{T} + KT - \hat{q} + (H + R)T = 0 \tag{7}$$

$$c_{p,e} = c_0 + \frac{L}{T_s - T_l} \text{ if } T_s \leqslant T \leqslant T_l \text{ or else } c_{p,e} = c_0 \tag{8}$$

At time zero, both the liquid and solid phases of the PCM were considered stationary. A no-slip boundary condition was applied at the interfaces of the PCM with the walls. The outer wall of the TES unit was assumed to be adiabatic, providing thermal insulation. Water entered the system under standard duct pressure conditions. Since the PCM was initially in its liquid form, the starting temperature was set at 65°C, while the inlet water temperature was kept at 14°C to model the chiller's water outlet temperature to study the solidification process under low cooling load conditions.

4. Results and Discussion

The present work provides a study assessing the performance of a cylindrical TES system featuring a helical pipe design filled with RT-42 and RT-35 PCM where the chilled water has been used as HTF using ANSYS/Fluent. This study evaluates the solidification of PCM at the chilled water flow rate of 10m/s. It involves monitoring key parameters, such as the outlet fluid temperature, PCM average temperature, and liquid fraction. The study utilized a three-dimensional heat transfer model based on the finite-volume approach, treating the PCM as an incompressible fluid during solidification. The inlet water enters at 14 °C from the chiller, where the PCM is fully melted with an average temperature of 65 °C. Figure 3 depicts the average temperature profiles of RT-42 and RT-35 during the solidification process with a water flow rate of 10 m/s. Initially, the PCM undergoes rapid sensible cooling from 45°C to 33°C. This is followed by a gradual temperature decrease from 33°C to 27°C, indicating the latent heat release phase during solidification in the case of RT-42. While RT-35 has a lower melting temperature than RT-42, it shows a transition in the phase less than RT-42 as the average phase transition remains from 27°C to 24°C, which will reflect the difference in outlet temperature and solidification time.

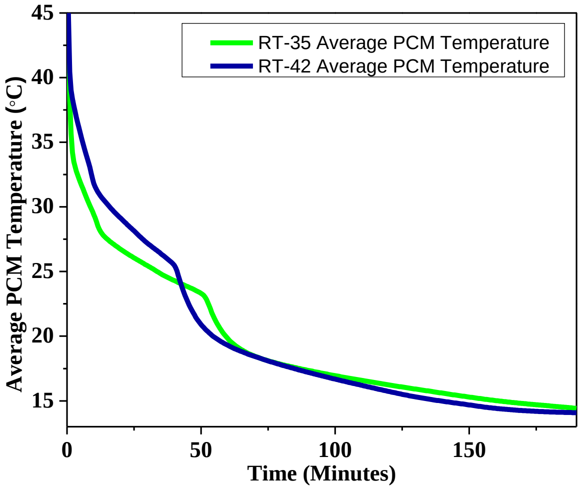

Fig. 3 Average PCM temperature

Figure 4 illustrates the evolution of the PCM's average liquid fraction during solidification, with inlet fluid at 14°C. The graph reveals rapid initial solidification, with 90% of the PCM transitioning to a solid state within the first 40 minutes in the case of RT-42 and RT-35 took relatively slightly more time. Subsequently, the solidification rate slows as the process continues through the remaining liquid PCM. This analysis provides insights into the solidification behavior of the PCM, highlighting the importance of system geometry and operation duration in TES applications. It also underscores the need for efficient heat transfer strategies throughout the solidification process.

The time required for solidification is the key factor for energy management, as it is very important to complete the solidification cycles in time to use cold energy during the peak hours. This study gives insight into how using different PCMs can optimize time and temperature requirements for effective energy management, peak shaving, and energy saving.

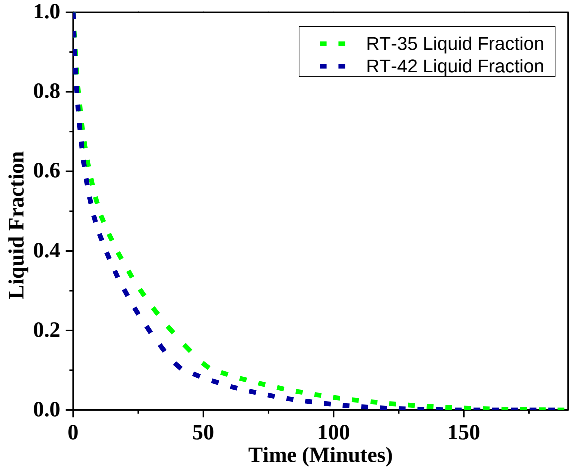

Fig. 4 Liquid fraction of RT-42 and RT-35

Figure 5 illustrates the changes in water outlet temperature when using RT-42 and RT-35 as the PCM. It demonstrates the effects of water flowing at 10 m/s with an initial temperature of 14°C. As the water passes through the system, its temperature increases due to heat exchange with the warmer PCM. This interaction causes the PCM to absorb the coolness from the water, leading to a gradual liquid-to-solid phase transition within the material. The temperature profile reflects the dynamic thermal energy transfer between the flowing water and the PCM during this process. RT-35 drops water temperature more, which can be significant in a large-scale system.

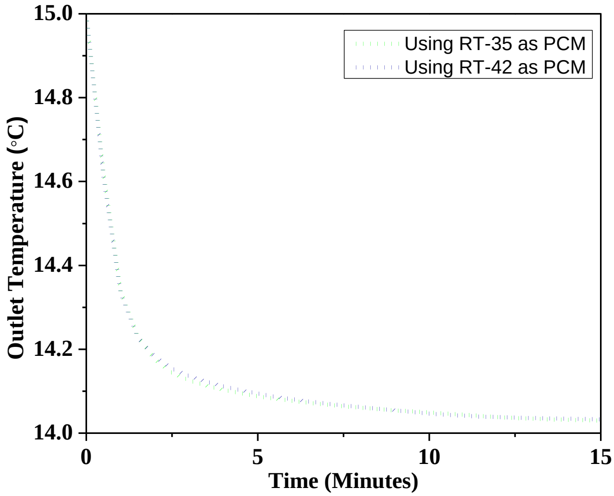

Fig. 5 Outlet temperature using RT-35 and RT-42 as PCM

Figures 6 to 11 show the melting fraction contours and comprehensively visualize the system's phase change dynamics of RT-42 and RT-35. These visual representations provide both temporal and spatial insights into the melting process. The contour plot effectively illustrates how the melting fraction evolves over time and varies across different areas of the studied region. This graphical depiction allows for a nuanced understanding of the phase transition patterns, highlighting areas of rapid melting and those where the process progresses more slowly. By visually presenting this information, the contours enable a more intuitive grasp of the complex phase change phenomena within the TES system. It can be observed that RT-45 solidifies faster than RT-35.

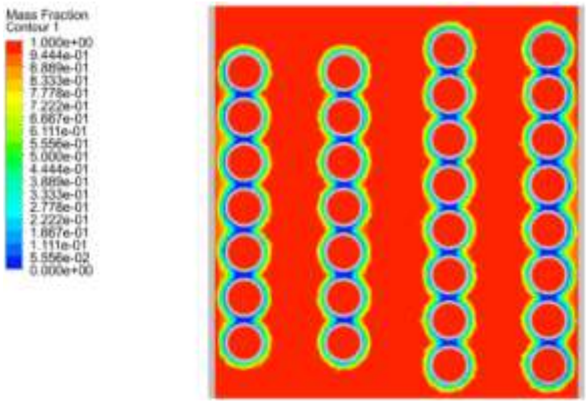

Fig. 6 Liquid fraction contours after 2 minutes RT-45

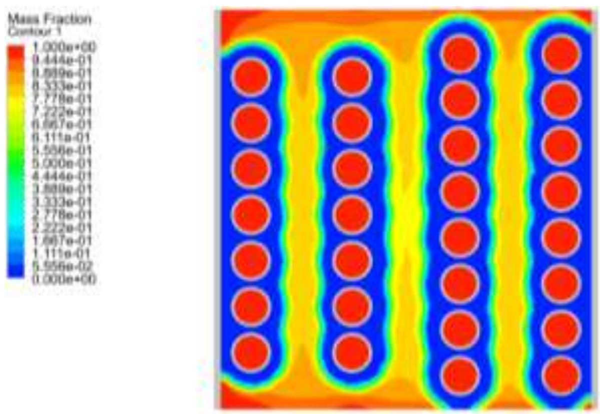

Fig. 7 Liquid fraction contours after 10 minutes using RT-45

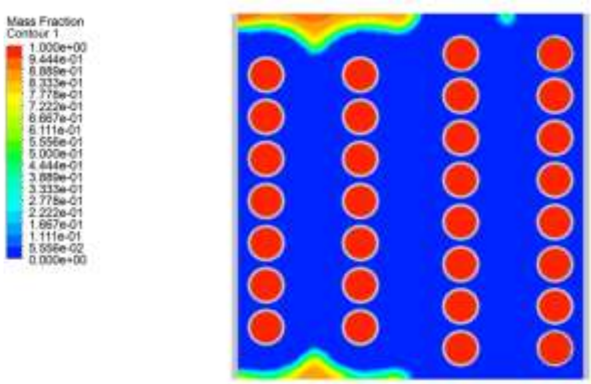

Fig. 8 Liquid fraction contours after 50 minutes RT-45

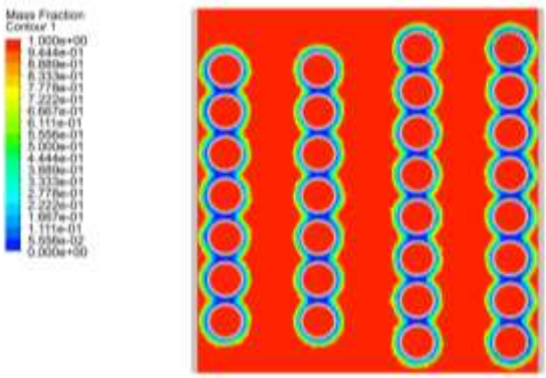

Fig. 9 Liquid fraction contours after 2 minutes RT-35

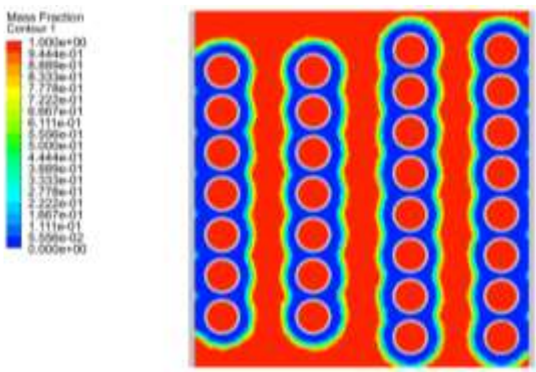

Fig. 6 Liquid fraction contours after 10 minutes RT-35

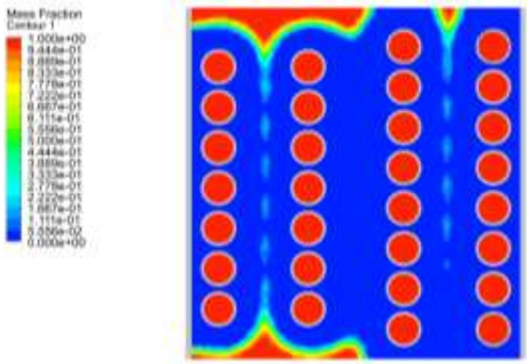

Fig. 7 Liquid fraction contours after 50 minutes RT-35

5. CONCLUSION

This numerical study provides a comprehensive analysis of a cylindrical TES system utilizing RT-42 PCM with a helical pipe design. The research focused on the solidification process of the RT-42 and RT-35 using chilled water as the heat transfer fluid, offering valuable insights into the system's performance and efficiency. Key findings from this study include:

1. Solidification Dynamics: The PCMs undergo rapid initial solidification, with 90% transitioning to a solid state within the first 40 minutes. The complete solidification process takes approximately 160 minutes in the case of RT-42 and 180 minutes in the case of RT-35, providing crucial information for system design and operational cycles.

2. Temperature Profiles: The study revealed distinct phases in the PCM's temperature evolution, including rapid sensible cooling followed by a more gradual decrease during the latent heat release phase. This highlights the high latent heat capacity of RT-42 and RT-35 and its potential for TES applications.

3. Heat Transfer Efficiency: The analysis of liquid fraction evolution and temperature profiles demonstrates the system's effective heat absorption capability. However, it also reveals the formation of a solid PCM layer that increases thermal resistance over time, suggesting the need for strategies to maintain efficient heat transfer throughout the solidification process.

4. System Performance: The water outlet temperature increased by a maximum of 1 °C, indicating efficient heat transfer with minimal impact on chiller performance. This supports integrating such thermal storage systems with existing chiller setups.

5. Design Optimization: The study suggests that adding an extra rotation to the helical pipe within the PCM-filled cylinder could significantly improve heat transfer rates, highlighting the potential for design enhancements.

This research contributes significantly to the field of TES, offering both practical design considerations and theoretical insights. The findings support the potential of PCM-based TES systems to enhance energy efficiency in building cooling applications. Such systems can reduce energy consumption and improve thermal management strategies by effectively storing excess cooling capacity.

Future research directions include exploring alternative PCM materials and optimizing system geometry. Additionally, experimental validation of the numerical models will be presented. In conclusion, this study demonstrates the promise of integrating TES systems with conventional building cooling equipment, paving the way for more sustainable and energy-efficient cooling solutions in the built environment.

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