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Original Article

Heat Transfer Simulation for Charging and Discharging of the Cold Thermal Energy Storage Using Phase Change Material

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Abstract - *In recent years, thermal energy storage systems have garnered significant interest from both researchers and engineers. They offer an appealing solution by addressing the disparity within the supply and demand of thermal energy as well as holding promise in improving the reliability and flexibility of power grids. Essentially, these systems function as a means of energy storage for future use in either heating or cooling purposes. This study presents charging and discharging analysis for cold thermal energy storage units using a phase change material through numerical simulation. Supported by experimental data, a comprehensive numerical analysis was done to evaluate the charging and discharging performance of PCM of a distinct latent thermal energy storage system. Emphasizing cargo preservation, the cold energy storage systems with PCMs were investigated to enhance stability at -18°C. The validated numerical model suggests that a 23% NaCl-water solution is optimal for Cold Thermal Energy Storage, enhancing heat storage and ensuring stable thermal power during phase transitions. The study's findings, including observed temperature plateaus, highlight the effectiveness of this solution in stabilizing cold room temperatures, offering valuable insights for PCM selection and system design to advance the field of thermal energy storage.*

Keywords - *Cold thermal energy storage, Cylindrical steel container, Experimental tests, Phase Change Material, Numerical modeling.*

1. Introduction

An increase in fossil fuel consumption has negatively affected climate change, causing global warming. This has been associated with the emission of greenhouse gases into the atmosphere, and it has become a great concern globally [1]. The rise in temperature due to climate change has accelerated the rate at which perishable foodstuffs such as vegetables and fruits are rotting, leading to food insecurity and money loss in return for the investment. A huge loss of post-harvest occurs probably due to either unavailability or lack of proper and efficient cold storage techniques in place. The conventional method, in this case, the use of refrigeration systems for food storage, consumes a lot of energy and power and also holds a low capacity of produce, which makes this method costly and unreliable on a large scale.

The transition of power generation from non-renewable to renewable sources is inevitable, and their adoptions are much encouraged owing to their economic and environmental benefits. Solar and wind energy sources are at the forefront of competing with other sources of renewable energy, but they are considered unreliable because they occur intermittently.

As attention shifts towards addressing global challenges related to food preservation and energy sustainability, cold thermal energy storage emerges as a critical area of focus. By leveraging PCM technology, cold storage solutions can mitigate food loss, enhance food security, and reduce energy consumption associated with traditional refrigeration methods. This has caused researchers and engineers to shift their focus towards designing and investigating Systems for storing thermal energy utilizing phase change materials. Thermal Energy Storage (TES) systems are likely candidates to provide a reduction in fossil fuel reliance while ensuring a reliable and stable energy supply [2].

Among TES technologies, particularly Latent Thermal Energy Storage system (LHTES) systems utilizing Phase Change Materials, can feasibly be used for heating or cooling purposes. Researchers [3] have extensively studied the application of PCMs for hot and cold energy storage systems experimentally and numerically. Literature [4] has revealed that the incorporation of PCM into TES systems results in an improvement in overall performance in terms of efficiency and energy storage capacity. The performance of the TES system depends on the careful selection of the PCM tank, thermal conductivity and heat storage capacity of the selected materials.

Recognizing the need for comprehensive energy solutions, Nishant et al. [5] paper highlights the importance of latent heat thermal energy storage systems in reducing fossil fuel usage and promoting renewable energy. Their study focused on optimizing LHTES heat exchangers, urging a shift towards studying real-world performance and system structure for practical use. Their work provides insights on various solar hot water systems incorporating LHTES, discussing future challenges and guiding researchers in developing energy-efficient solutions.

Marcel et al. [6] investigate the performance of a heat pump system at a green-field dairy in Bergen, Norway. The system uses innovative high-temperature heat pumps and meets heating and cooling demands efficiently.

Binjian et al. [7] characterized phase change material for Storing thermal energy in the transport air conditioning. Through experimental measurements, transient and overall heat transfer coefficients are quantified, and empirical relationships between non-dimensional numbers are established. These relationships are validated through further experiments, showing agreement within 2.33% and 1.65% for charging and discharging processes, respectively. This study represents a pioneering effort in understanding the behavior of PCM-based TES devices.

Oro et al. [2] analyzed thermal energy storage by using solid-liquid phase change materials for cold storage applications. The analysis identifies more than 88 potential PCM possibilities that are acceptable for low-temperature settings, with approximately 40 choices that are commercially accessible. In addition, the study examines important factors, including PCM encapsulation techniques, approaches to optimize heat transfer, and food quality in relation to storage systems. The authors attempted to address the long-term stability concerns related to PCM materials, which include corrosion and phase segregation. Additionally, the study involves evaluating heat transmission pathways through both theoretical and experimental approaches.

Liu et al. [8] investigated the incorporation of PCMs into refrigeration systems for trucks. Their study found that the inclusion of PCMs with a melting point of -26.7 °C resulted in a decrease in energy costs by 86.4%.

Zivkovic et al. [9] examined the use of PCMs via CFD simulations of containers with different shapes. Their CFD models were verified by comparing the obtained results with experimental results. Their analysis largely concentrated on the several methods of heat transmission, specifically examining conduction within PCM with directed vectors of moving fronts, as well as convection outside the PCM, including airflow and the thermal conductivity of materials. The reduction in storage volume was more noticeable in air-based systems as opposed to liquid-based systems. Enthalpy-based approaches were frequently utilized for computations, demonstrating a linear rise in temperature, followed by a period of stability and then a parabolic increase. Their work examined the charging and discharging operations of cold thermal energy storage units using PCM by numerical analysis.

Diarce et al. [10] carried out Computational Fluid Dynamics (CFD) simulations on a ventilated façade model that incorporates PCM. PCM was exclusively applied to the external surface. The work entailed a comparison between numerical models and experimental validation, with a specific focus on the behavior of PCM in its solid state. The energy efficiency of the ventilated façade was enhanced by incorporating a low-temperature diffusivity exterior layer.

Tests were performed on a ventilated dynamic façade that included PCM. The findings of computer simulations were compared to the experimental data collected over the same time period. An investigation was conducted to examine alterations in convection heat transfer by analyzing flow fluctuations at various velocities. Temperature monitoring of the PCM, the inner side, and the external layer was implemented. Comparisons were made between the outcomes of transient simulations and actual experimental data, resulting in a decrease in simulation time. The ultimate model demonstrated its suitability in optimizing the performance of building exteriors in turbulent situations.

Tay et al. [11] performed a practical examination of TES using PCM in four tubes organized in a cylindrical manner. The authors targeted to enhance the efficiency of charging and discharging durations while ensuring the effectiveness of TES is within the acceptable parameters. PCM storage was discovered to provide more energy density as compared to sensible heat storage. In their study, the four tubes were vertically aligned and installed with Resistance Temperature Detectors (RTDs) in addition to thermocouple connections. They performed experiments at room temperature to replicate freezing processes. Analysis was conducted at three distinct locations, and the comparison between the experimental and computational fluid dynamics model output data demonstrated consistency.

Martina et al. [12] analyzed the charging and discharging processes of PCMs' distinct units for storing cold thermal energy. This was done through numerical simulations. According to the authors, the first unit consisted of a cylindrical container made of aluminum material, and it was partially filled with a biological PCM. In contrast, the second unit had an extra layer of aluminum metal foam within the PCM. The effective heat capacity method was employed to build two-dimensional axisymmetric models that incorporate the latent heat of PCM. The models were evaluated against experimental data collected from a climate chamber in order to identify the most suitable set of model parameters. The results showed important findings: in the unit containing only PCM, the charging process is mainly affected by conductive heat transfer in the presence of a thermally resistant layer of solid PCM having a considerable impact. On the other hand, Natural convection is essential for facilitating the discharge procedure. In contrast, the device equipped with PCM and aluminum foam exhibited significantly accelerated charging.

Talukdar et al. [13] research investigates a thermal energy storage device that utilizes phase change material as a backup for storing cold energy generated by solar power. The analysis of PCM solidification and melting within the LHTES unit is conducted using numerical simulations that are validated by experiments. Various evaporator layouts are investigated to get the dynamics understanding of charging and discharging. According to the authors, computational fluid dynamics simulations demonstrate that an increase in the number of fins in a PCM pack improves the process of solidification, increases the capacity for energy storage, and enhances the heat flux during the melting phase.

Previous studies [14] explored various aspects of system performance and optimization of systems using PCMs. Few studies [15-17] focused on developing mathematical models to predict the thermal properties of PCMs at low temperatures, taking into account factors such as phase change behavior and material composition. Additionally, numerical simulations have been valuable tools for analyzing heat transfer and optimizing system performance. However, there are still inadequate studies that focus on the validation of these simulation models using experimental data, particularly for cold thermal energy storage systems or freezers. Conducting experimental validation studies under controlled cold room conditions is crucial to providing essential validation data and ensuring the accuracy of simulation models. Furthermore, some studies may have overlooked convective heat transfer on the PCM module surface in frozen cold room applications. Addressing these gaps in the current body of literature will contribute to a better understanding of CTES system dynamics and optimization, ultimately improving energy efficiency in cold storage units.

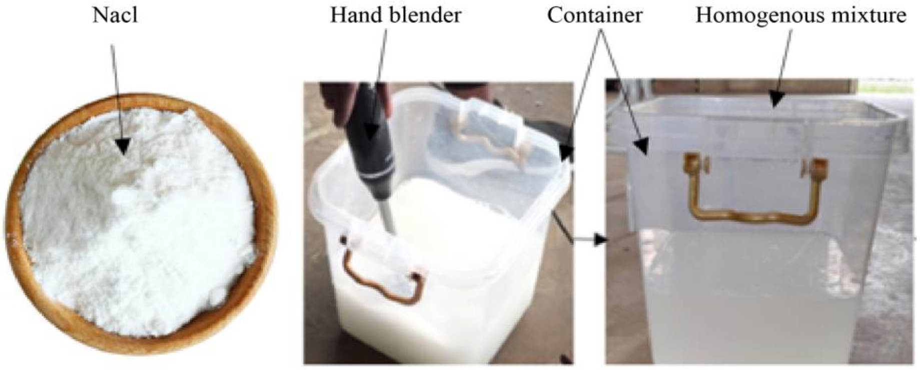
2. Study Significance

This study aims to contribute by addressing global challenges in food preservation and energy sustainability through incorporating PCMs for the design of of cold thermal energy storage systems. Through rigorous numerical simulations and experiments, the study offers valuable insights into PCM-based cold storage units' thermal behavior and efficiency, particularly at -18°C. Identifying a 23% NaCl-water solution as optimal for stabilizing cold room temperatures when using affordable and available stainless steel material. The study provides actionable insights for enhancing energy efficiency and promoting sustainable development in cold storage applications.

3. Experimental Method

3.1. Experimental Setup

Two sets of experiments were conducted. The first set aimed to ascertain the thermophysical properties of the NaCl-Water, which was used as a phase change material, while the second set aimed to discover the charging and discharging rate of the same material. This was compared with water. To optimize PCM charging and discharging durations and observe heat transfer distribution, uniform amounts of PCM were used for concentrations ranging from 20% to 24%, and a eutectic solution of sodium chloride (NaCl) with a concentration of 23% was used. The solution was prepared by mixing 0.932 kg of sodium chloride and 4 litres of water, as illustrated in Figure 1.



(a) PCM NaCl **(b) PCM solution mixture** **(c) Homogenous mixture**

Fig. 1 Eutectic solution preparation

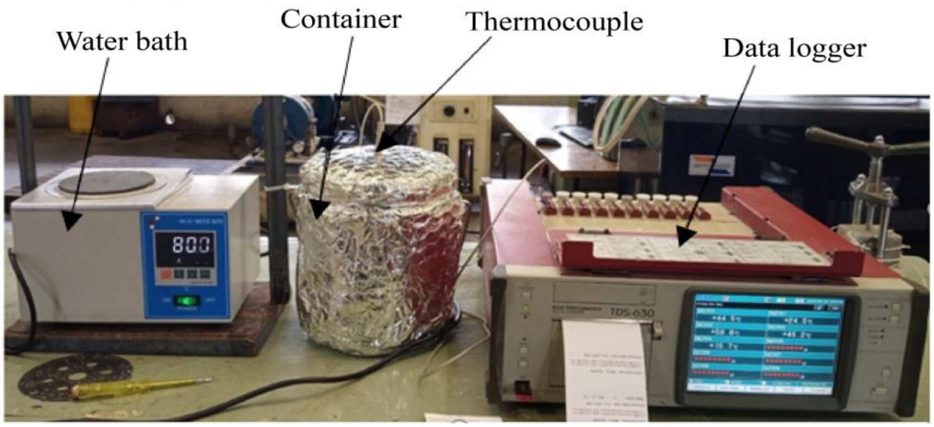


Fig. 2 Specific heat capacity test

3.2. Thermophysical Properties of Phase Change Material

The thermo-physical characteristics, including specific heat capacity, density, and latent heat, of the synthesized PCM solution were measured. These properties are crucial in assessing the performance and suitability of the PCM solution for specific applications.

3.2.1. Density

The PCM solution density was computed using the volume displacement method. A graded cylinder with a capacity of 100-1000 ml and intervals of 500 ml was utilized. The sample's mass was determined using a precise electronic balance with an accuracy of ± 10 °C. The measurements were conducted in triplicate.

3.2.2. Specific Heat Capacity

The specific heat capacity was determined using the set-up shown in Figure 2. The PCM solution was prepared for us to explain early. A digital water bath was set up and fill with an insulated container with one kilogram of clean water. The initial temperature of sodium chloride was measured using a thermometer with an accuracy $\pm$ 0.5. One-kilogram salt solution was placed in a water bath and raise the temperature to the desired set temperature. For stabilization, wait left for 5 minutes. The after voltage and current were measured to determine the heat energy during heating. The heated solution was poured into the insulated container, and a temperature measure was used using a thermocouple connected to a data logger. The measurement was done after intervals of two minutes until thermal equilibrium was reached. Using Equation 1, the specific heat capacity was calculated using Equation (1) [18].

$$Q = m * c * \Delta T \qquad (1)$$

Where Q is heat energy, m is mass, c is specific heat capacity, and ΔT is temperature range.

3.2.3. Latent Heat of Fusion

The Latent Heat was determined using the set-up shown in Figure 3. The setup involved several key components: a scale, an insulated container, a data logger, and a thermocouple. The experiment began by measuring the mass of the calorimeter, which was then filled halfway with water maintained at a temperature 10°C above room temperature. Ice cubes were introduced into the water until the mixture reached a uniform temperature of 0°C.

Initial temperatures were recorded before introducing the ice and after reaching the 0°C equilibrium. Crushed ice was continuously added until a consistent 20°C temperature drop was achieved in the mixture. Using Equation 2, the Latent Heat of Fusion was calculated using Equation (2) [19].

$$m_i l + m_i C_w \Delta\theta_1 = m_w C_w \Delta\theta_2 \qquad (2)$$

Where l is the latent heat of fusion, C_w specific heat capacity of water ($\Delta\theta_1$,$\Delta\theta_2$) are temperature changes considered.

3.2.4 . Charging and Discharging Setup

The charging and discharging setup involves placing a solution in a container of steel and subjecting it to a freezing process within a freezer for 48 hours to charge. Following this, the container is removed, allowing the solution to discharge as it warms outside the freezer. This straightforward approach serves as a practical method to observe the thermal behavior of the solution, offering insights into its charging and discharging characteristics.

3.3 CFD Simulation Method

The advancement in computer technology and architecture has propelled the popularity of Computational Fluid Dynamics simulations among researchers for predicting the heat flow behavior of Phase Change Materials.

This methodology offers cost-effectiveness in terms of labor and time compared to traditional experimental methods. However, assessing the accuracy of obtained results requires validation to ensure that the employed approach yields acceptable levels of precision and reliability.

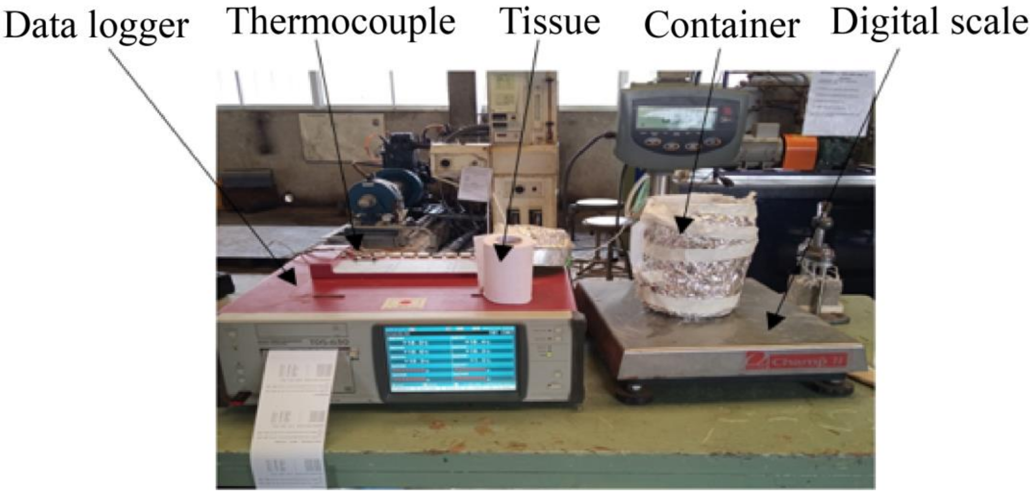
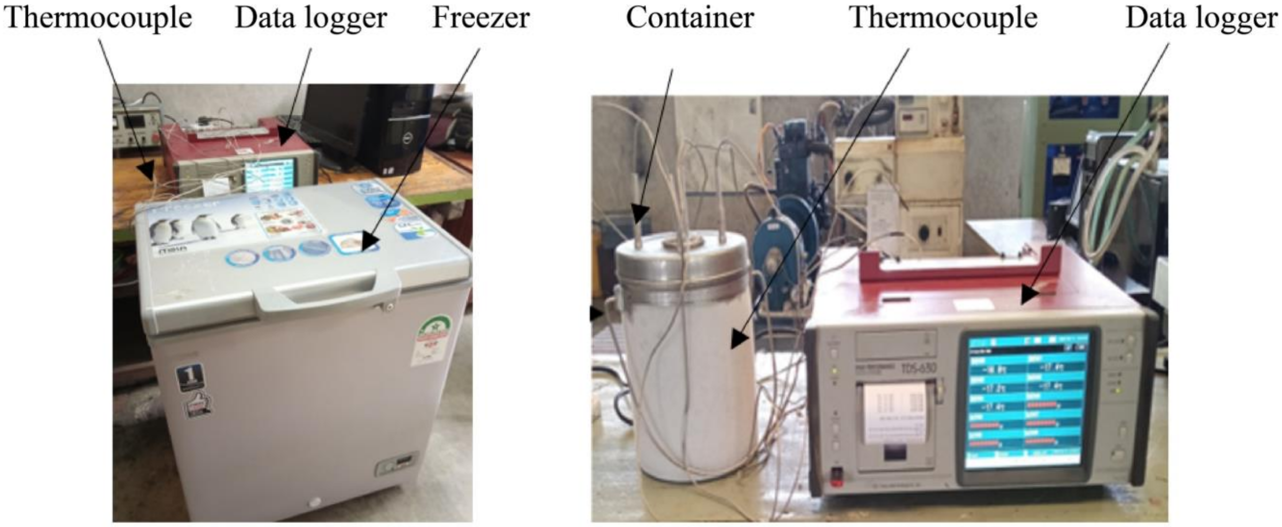


Fig. 3 Latent heat test



(a) Charging solution **(b) Discharging solution**

Fig. 4 Charging and discharging test

In this study, the ANSYS Fluent software was applied to forecast the charging and discharging behavior of PCM, specifically Sodium Chloride Hydroxide. The focus of this paper lies in validating the CFD predictions by comparing them with experimental results. All CFD simulations were executed on an i7 laptop equipped with a 64-bit Microsoft Windows 11 Pro operating system. The laptop boasts 16.0 GB RAM and an AMD Ryzen 7 3700U processor clocked at 2.30GHz. Notably, this setup possesses the capability to handle CFD projects, with all governing equations for mesh elements limited to 5 million, without encountering issues of occupied virtual memory during simulation

3.3.1. Pre-processor

In this stage, two tasks were conducted. Firstly, the simulation domain was constructed using ANSYS Designer Modeler, and secondly, the domain was subdivided using the ANSYS Mechanical program for meshing purposes. This research endeavours to replicate experimental data by utilizing the same container employed in the experiments, as depicted in Figure 5***Fig. 5***. The container, constructed from stainless steel, features a top cover. However, stainless steel is recognized for its low heat conduction coefficient, prompting this investigation into its performance concerning the charging and discharging of PCM to evaluate its suitability for cold thermal storage.

The container in question was cylindrical, with a diameter of 184 mm and a height of 203 mm. To streamline the CFD simulations, a two-dimensional analysis based on the axisymmetric method was adopted, and the fluid domain was simplified accordingly, as illustrated in Figure 6.

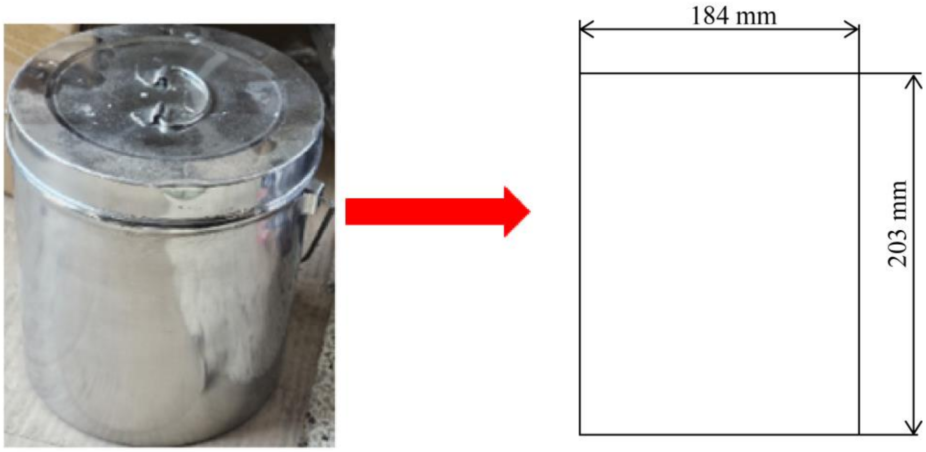


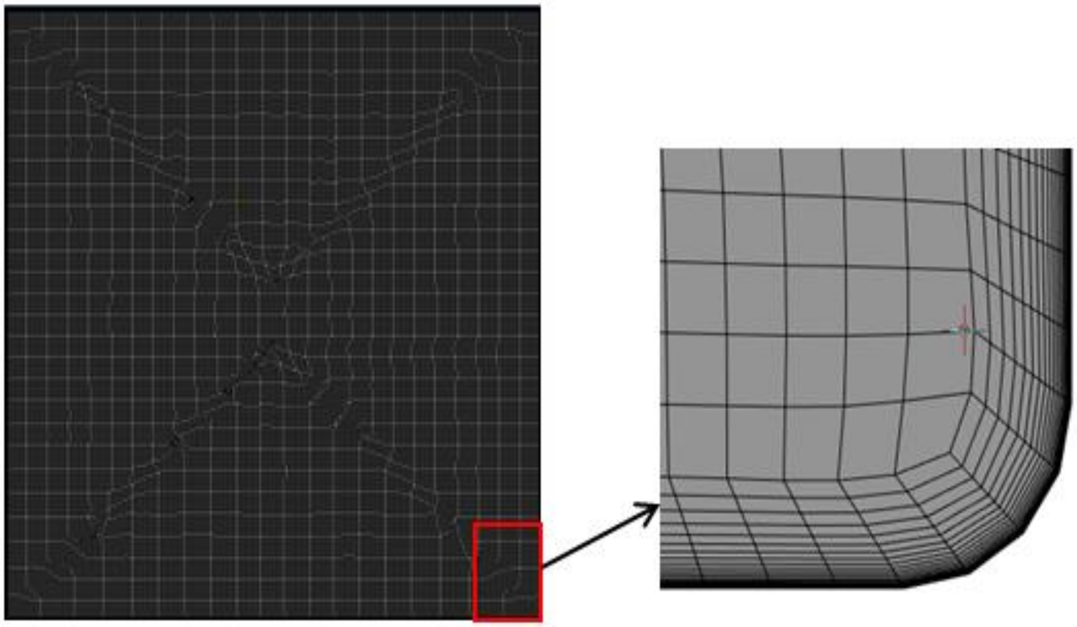
Fig. 5 PCM simulation domain

The plane at the center was remodeled in CAD software (ANSYS Design Modeller). It was chosen to reveal a balanced insight into heat transfer behavior on charging and discharging of PCM. The finite volume method was applied, and the simulation fluid domain was discretized into small controlled volumes using a mechanical mesh programme in ANSYS. Several mesh sizes for different simulations were carried out, as indicated in Table 1, in order to determine convergence of grid size. The bulk of mesh cells are structured as demonstrated in ***Fig. 6***Figure 6.

On meshing, more emphasis was centered near the wall, which acts as an interface between the surrounding and PCM inside the container. To improve the accuracy of the heat transfer through the wall to PCM, an inflation of 20 layers was inserted near the walls of the container, including the cover. ***Fig. 6***Figure 6(a) and (b) show obtained mesh grids for 2D. Moreover, Figures 6, and 7 shows the different variations of mesh with changes in mesh size (10mm, 5mm,2.5mm and 1mm).

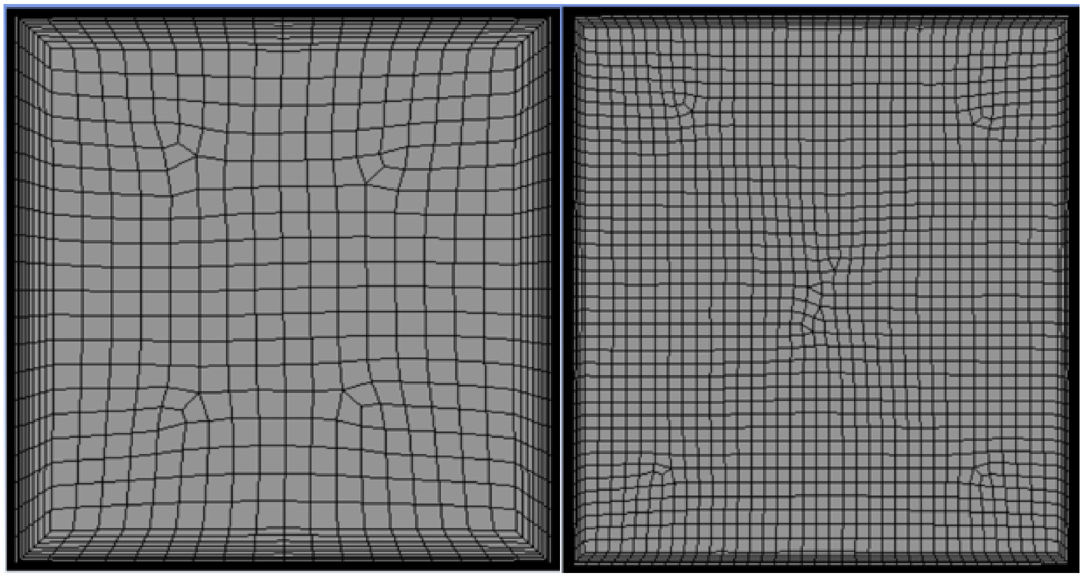
Table 1. Mesh independence study

Mesh Size (mm)	**Number of Element**	**Number of Nodes**	**Number of Time (min)**
10mm	1848	1887	50 min
5mm	4529	4608	100 min
2.5mm	12085	11929	150 min
1mm	51850	51490	230 min

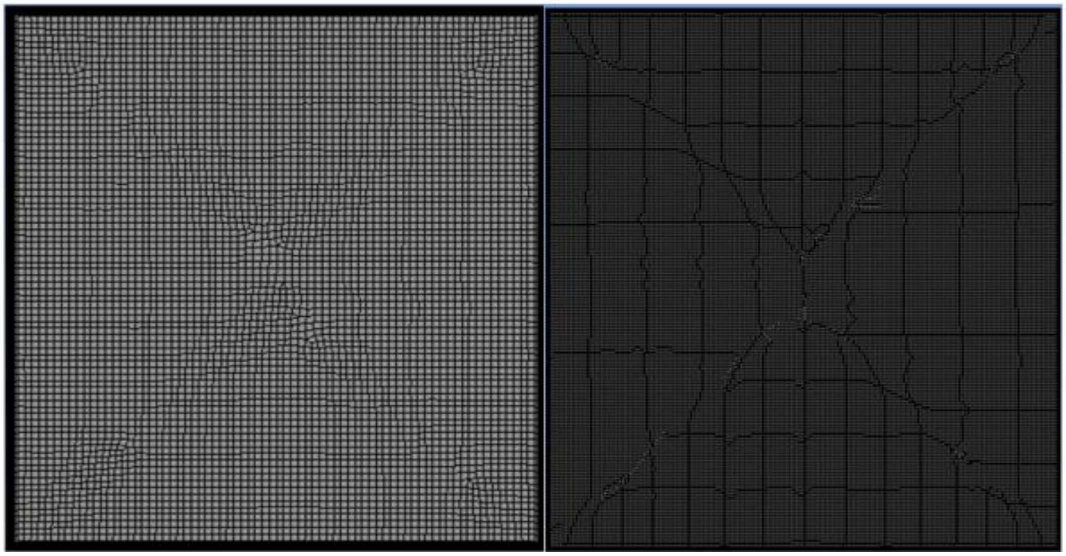


(a) **(b)**

Fig. 6 Generated mesh



(a) 10mm **(b) 5mm**



(c) 2.5mm **(d) 1mm**

Fig. 7 Variation of mesh with change in mesh size

3.3.2. CFD Setting and Computation

This is referred to as a solver stage, where the necessary parameters are considered and set up into ANSYS FLUENT. The 2D analysis was chosen with double precision in an attempt to reduce uncertainty due to the computational limit of virtual memory in a laptop. The mesh was partitioned into four equal parts and was solved simultaneously. All governing equations were solved using the finite volume method. Since the PCM fluid remains static in the container, the laminar model was used under Reynolds Average Navier Stoke (RANS) to compute and solve governing equations.

The pressure and velocity variables were coupled using the segregated method that is formed under the SIMPLE algorithm. All momentum and energy convective and diffusion terms were discretized using second-order upwind and truncated at second-order. PRESTO approach was utilized to spatially discretize pressure while all gradients were done using a least squares cell-based scheme. The convergence conditions were monitored using residual tolerance, where continuity and velocity variables were set to converge at 10^{-6}. This would ensure the computation is satisfactory and prevent it from stopping before convergence. Apart from that, the temperature change in PCM was also monitored. Standard initialization was applied in all simulations. The calculations were run using a transient scheme since charging and discharging vary with time. A fixed time of 1440 number of time steps was set, where a maximum of 10 iterations was used for every time step.

3.3.3. CFD Governing Equations

The transition of PCM from its solid to liquid phase during charging and discharging is regulated by the principles of mass, momentum, and energy conservation for stationary PCM. The overarching mathematical equations governing these processes are derived from FLUENT [20].

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho v) = 0 \qquad (3)$$

Conservation of Linear Momentum

$$\rho\left[\frac{\partial \vec{V}}{\partial t} + (\vec{V}.\nabla)\vec{V}\right] = -\nabla p + \mu\nabla^2\vec{V} + \rho\vec{f} \qquad (4)$$

Energy conservation

$$\rho\left[\frac{\partial h}{\partial t} + \nabla.(h\vec{V})\right] = -\frac{Dp}{Dt} + \nabla.(k\nabla T) + \emptyset \qquad (5)$$

3.4. Boundary Conditions

3.4.1. Thermophysical Properties of PCM

Table 2 shows the thermophysical properties of PCM used for the 2D model.

Figure 8 shows the Boundaries and boundary conditions for the CFD simulation under study. The "S" denote the surface or wall and the subscript number indicates the numbering of the walls.

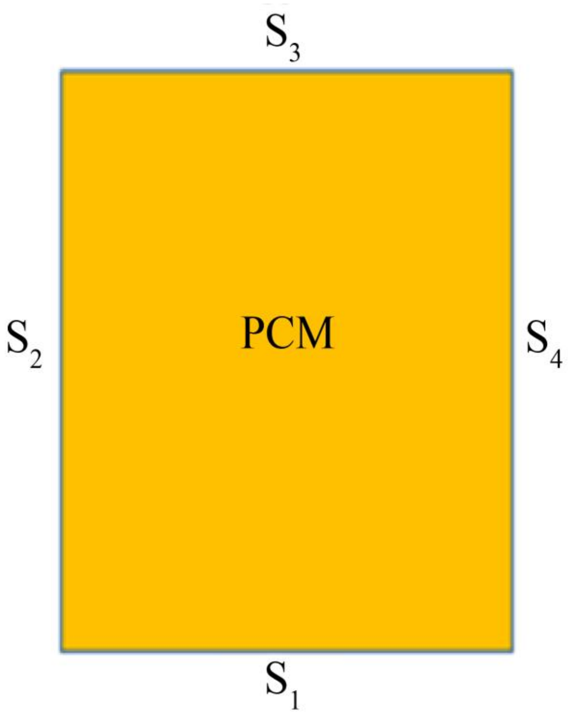


Fig. 8 Boundary conditions

Table 2. Thermophysical properties of PCM used for 2D model

Properties PCM	Water	Ice	Charging salt 23%	Discharging salt 23%
Density (Kg/m^3)	998	915	1180	1180
Specific Heat (J/Kg-k)	4182	2000	3270	3270
Thermal conductivity (W/m-k)	0.61	1.15	0.32	0.35
Latent heat of fusion (kJ/Kg)	33376	33551	246600	246600
Solidus temperature °C	0	0	-21.7	-21.7
Liquids temperature °C	0	0	-21.7	-21.7

Steel properties thermal-physical		
Density (Kg/m^3)	Specific Heat (kJ/kg K)	Thermal Conductivity (W/mK)
8030	502.48	16.27

The boundary condition for S_2 and S_4 are similar and for S_3 and S_1 the temperature are different.

$$-k\frac{\partial T}{\partial x}|S_2, S_4 = 0 \qquad (6)$$

$$-k\frac{\partial T}{\partial y}|S_3 = TS_3 \qquad (7)$$

$$-k\frac{\partial T}{\partial y}|S_1 = TS_1 \qquad (8)$$

Table 3. Boundary conditions of PCM

Charging	Temp	Discharging	Temp
Top wall (S_3)	-24	Top wall (S_3)	23.3
Left wall (S_2)	-22	Left wall (S_2)	23.3
Right wall (S_4)	-22	Right wall (S_4)	23.3
Bottomwall (S_1)	-22	Bottomwall (S_1)	17.8
Thickness	0.002	Thickness	0.002

4. Results and Discussions

4.1. Results

4.1.1. Thermophysical Properties Characterization

Table 4 illustrates the thermal properties of PCM for water and for the different concentrations of salt.

Temp: Temperature

Table 4. Thermal properties of PCM

Concentrations (%)	**Latent heat (kJ/kg)**	**Specific Heat (kJ/kg K)**	**Density (Kg/m^3)**
H_20	333.76	4182	998
20%	306.91	3807.37	1160.01
21%	283.41	3796.61	1169.61
22%	261.77	3764.70	1176.33
23%	246.60	3699.51	1180.46
24%	226.21	3250.88	1192.93

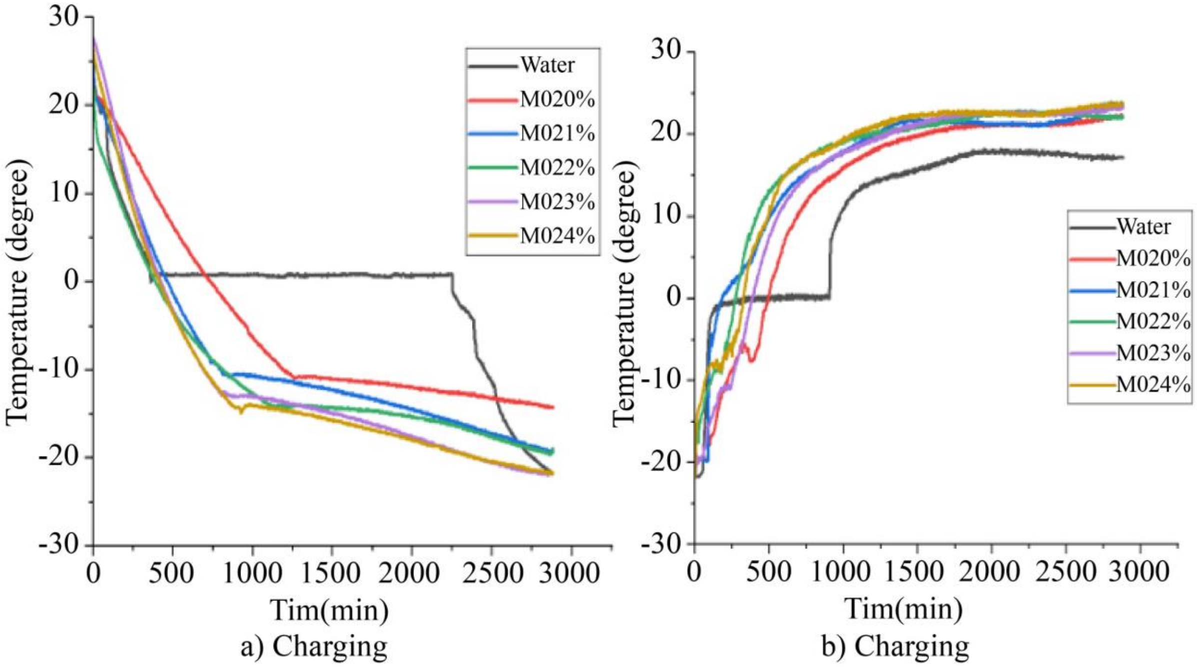


Fig. 9 Charging and discharging PCM water and NaCl test

4.1.2. Charging and Discharging PCM

Fig. 9Figure 9 illustrates the temperature profiles of water and NaCl-water solutions with different concentrations during the discharging and loading processes, which correspond to the freezing and melting cycles of PCMs in a cold storage application.

Table 5 illustrates the thermal properties of PCM for water and freezing temperature for the different concentrations of PCM.

Table 5. Freezing temperature for difference concentration PCM

Concentration (%)	**Freezing (°C)**	**Freeze (Time)**	**Low temp (°C)**
H_2O	0	2248	-21.7
20%	-10.7	1288	-16.8
21%	-11.0	1092	-19.3
22%	-14.0	1158	-19.5
23%	-12.9	920	-21.7
24%	-14.1	970	-20.5

The table detailing the thermal characteristics of various PCMs at different concentrations is valuable for TES research. Several important findings emerge from the data. Firstly, there’s a notable decrease in melting temperature as PCM concentration increases from 20% to 23%, reaching an optimal -21.7°C suitable for a -18°C environment. However, at 24%, the melting point rises slightly to -20.5°C, possibly due to eutectic behavior. Secondly, there is a consistent decrease in latent heat with increasing concentration, impacting energy storage capacity during phase change. While higher latent heat is typically preferred for TES, this underscores the significance of concentration.

Thirdly, specific heat experiences a slight decline with concentration, affecting the energy required to maintain temperature. Finally, density increases with PCM concentration, potentially enhancing energy storage capacity per unit volume. These insights provide a comprehensive understanding of PCM behavior crucial for maximizing the efficiency of cold TES systems.

Figure 9(a) shows the temperature decrease over time as solutions emit heat into the environment, indicating the solidification of PCM from liquid to solid state. This process releases heat to the environment or stored items. It begins with a rapid drop in temperature from 28°C to 0°C, followed by a plateau phase lasting from 0 to 2450 minutes, during which latent heat is released without significant temperature change. NaCl incorporation facilitates phase transition below 0°C, resulting in lower temperatures with higher NaCl concentrations.

Figure 9(b) illustrates the temperature increase over time as solutions absorb heat from the environment, representing PCM melting from solid to liquid state in cold storage systems. All solutions, even pure water, start below their freezing points and quickly increase in temperature. A plateau phase indicates the phase change from solid to liquid, with NaCl solutions undergoing changes below 0°C due to salt's freezing point depression effect. Higher NaCl concentrations correlate with lower plateau temperatures.

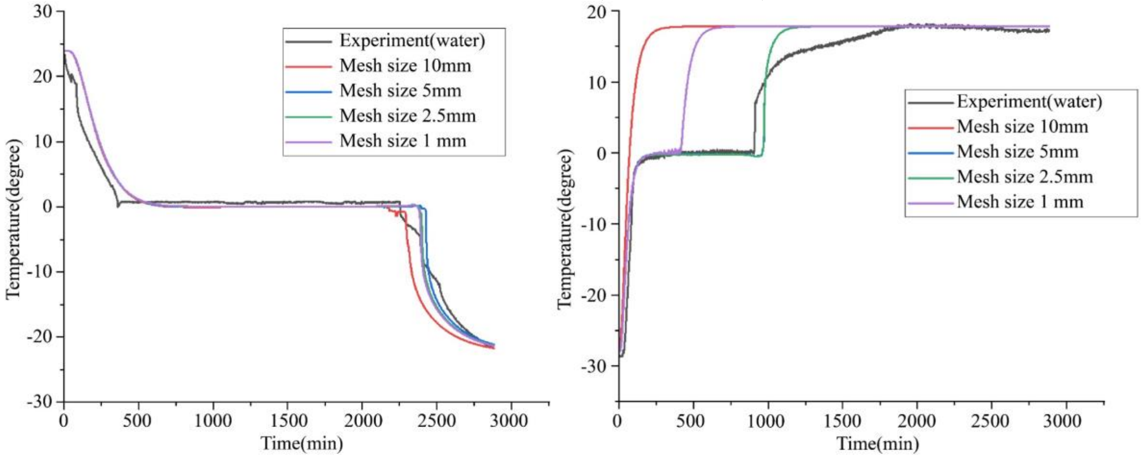
4.2. CFD Mesh Sensitivity and Validation

In the realm of Computational Fluid Dynamics simulations for thermal energy storage systems, the accuracy of results hinges significantly on the mesh resolution employed. Mesh sensitivity analysis and validation serve as crucial steps in ensuring the fidelity of numerical simulations. By varying the mesh sizes, such as 10mm, 5mm, 2.5mm, and 1mm, the study aims to investigate the impact of mesh resolution on the charging and discharging processes within a Phase Change Material-thermal Energy Storage module. This exploration will provide insights into how different mesh resolutions affect the simulation outcomes, aiding in the determination of an optimal mesh size for accurate and reliable predictions.

4.3. PCM Charging Process

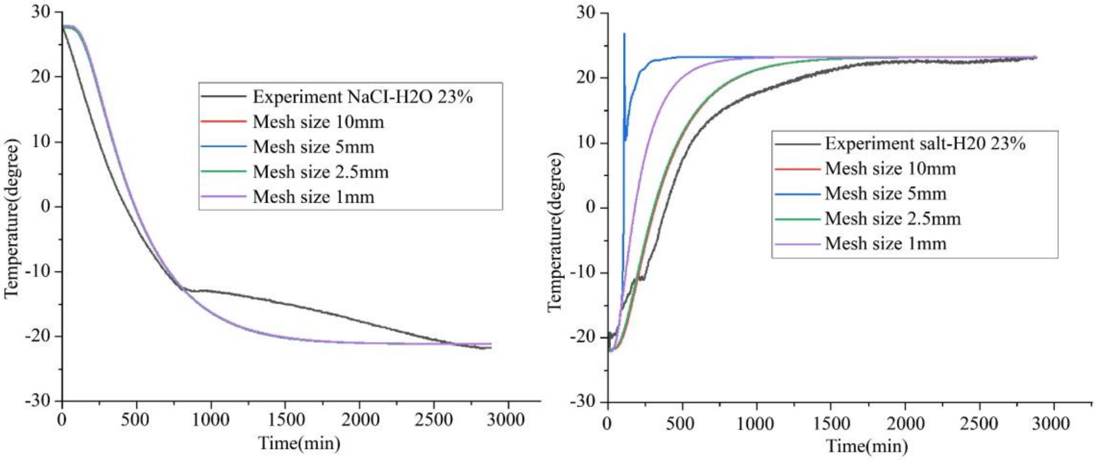
4.3.1. Charging Times for Water and NaCl-H_2O

Figures 12 ***Fig. 12*** to 15 depicting the simulated temperature and melting at five distinct times during the charging phase of the cold storage unit containing PCM (Distilled water) and NaCl-water.



(a) **(b)**

Fig. 10 Temperature charging and discharging H_2O



(c) **(d)**

Fig. 11 Temperature charging and discharging NaCl-H_2O

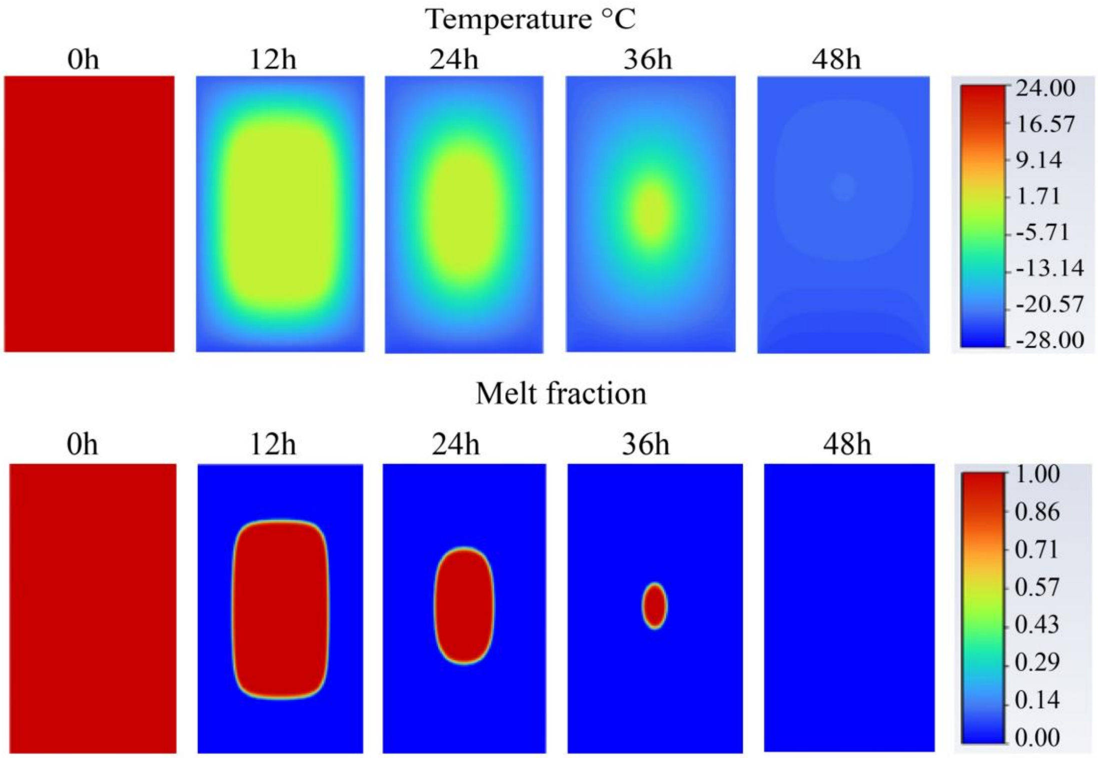


Fig. 12 Charts depicting the simulated temperature and melting at five distinct time points during the charging phase of the cold storage unit containing PCM (Distilled water)

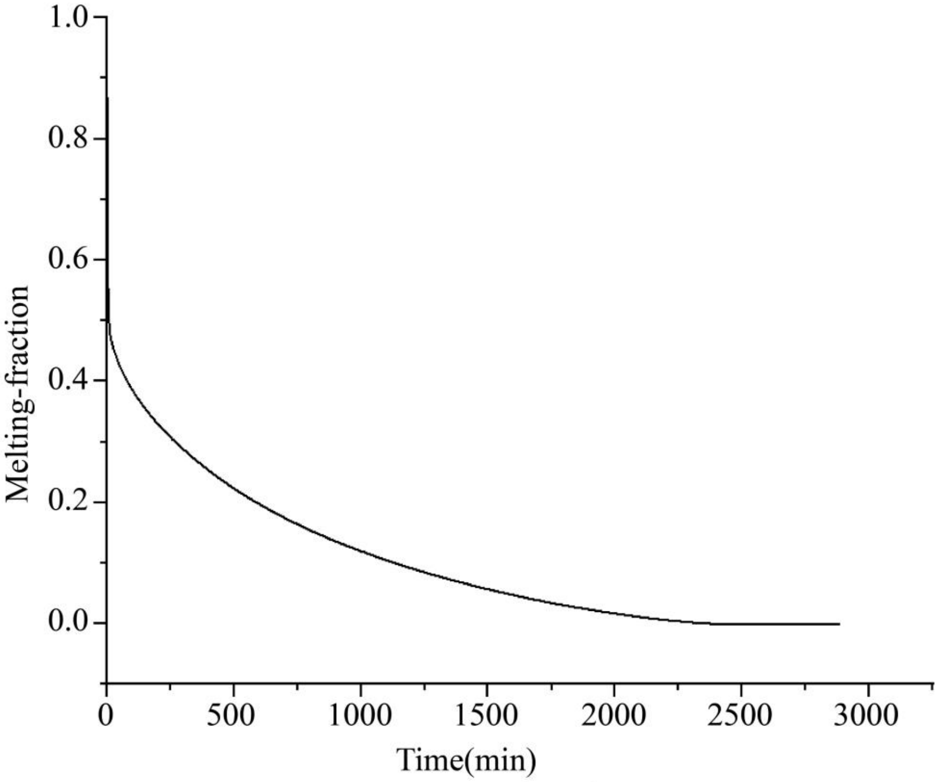


Fig. 13 Melting fraction charging H_2O

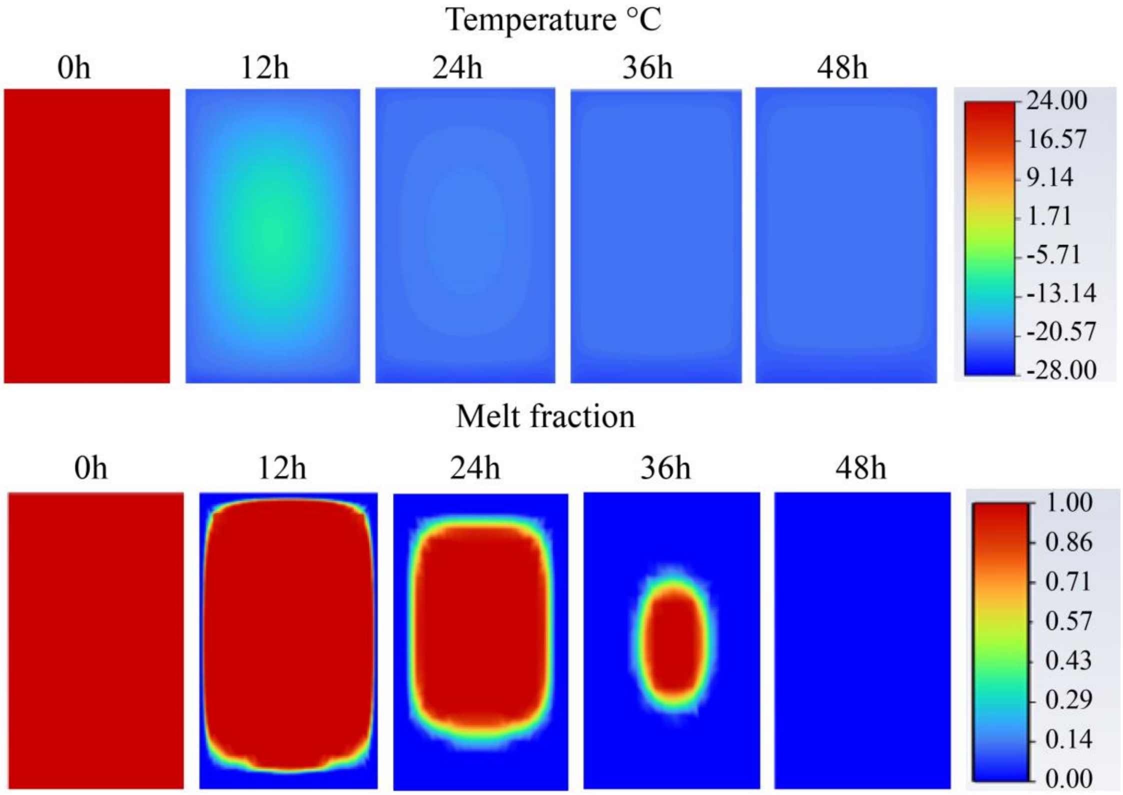


Fig. 14 Charts depicting the simulated temperature and melting at five distinct time points during the charging phase of the cold storage unit containing PCM NaCl-H_2O

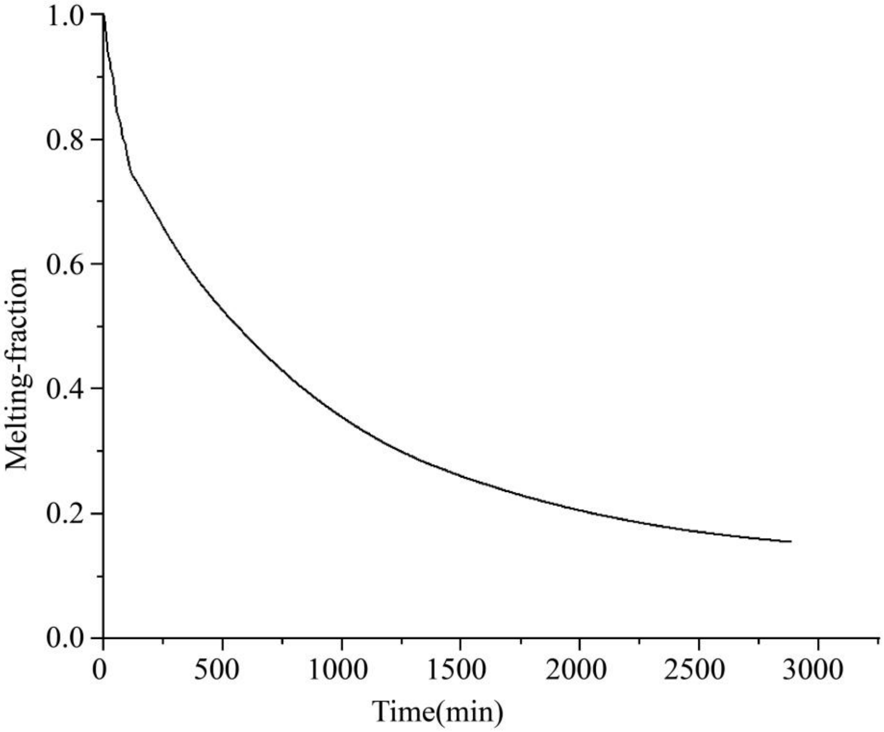


Fig. 15 Melting fraction charging NaCl-H_2O

The charging temperature profiles for distilled water and a 23% salt-water solution demonstrate in ***Fig. 12***Figure 12 to Figure 15 demonstrate precise alignment between actual and simulated data, validating the precision of the simulation. The graphs show an initial rapid temperature decrease, a plateau at 0°C indicating the phase change, and a subsequent decline as freezing continues. Design implications involve optimizing container geometry and materials for a more uniform and efficient freezing process, enhancing system performance. The simulation's accuracy in predicting phase change behavior is emphasized, underscoring the critical role of representing the plateau in phase change dynamics. Additionally, insights from a separate graph on the melting fraction of distilled water contribute to optimizing the TES system design and addressing efficiency concerns related to the extended freezing of the final liquid portions.

4.4. PCM Discharging Process

4.4.1. Discharging Time for Water and NaCl-H_2O

Fig. 16 Figure 16 to 19 illustrate depicting the simulated temperature and melting at five distinct times during the discharging phase of the cold storage unit containing PCM (Distilled water) and NaCl-H_2O.

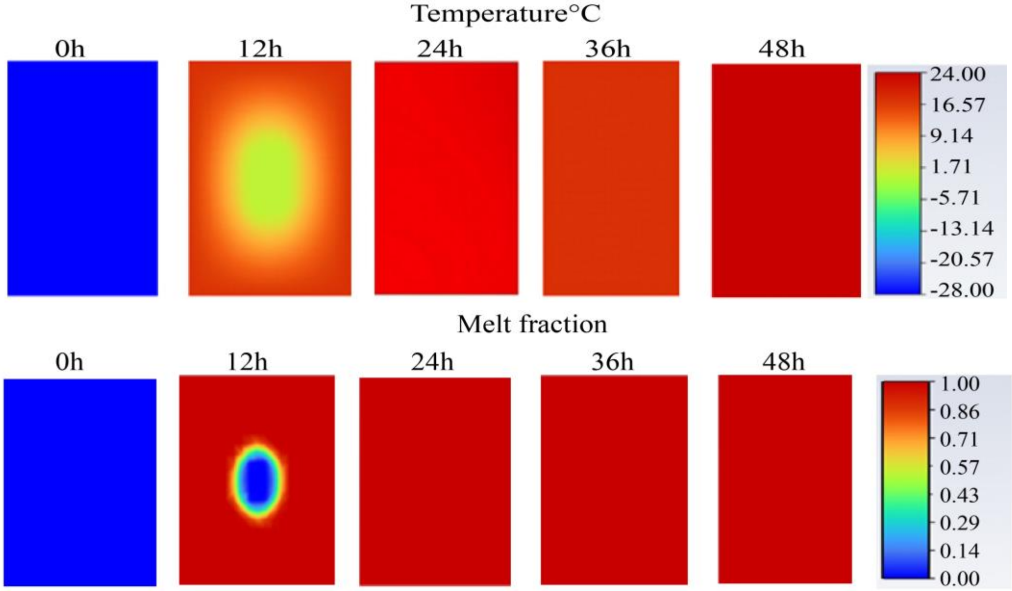


Fig. 16 Charts depicting the simulated temperature and melting at five distinct time points during the charging phase of the cold storage unit containing PCM (Distilled water)

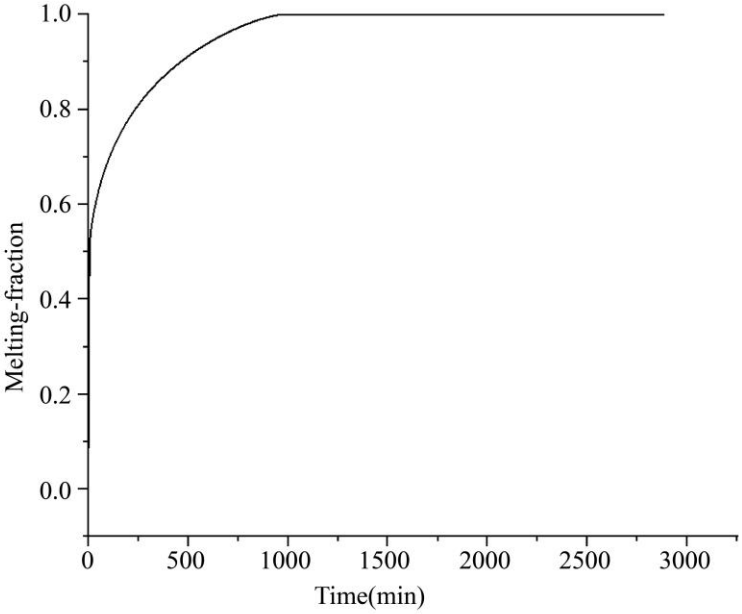


Fig. 17 Melting fraction discharging H_2O

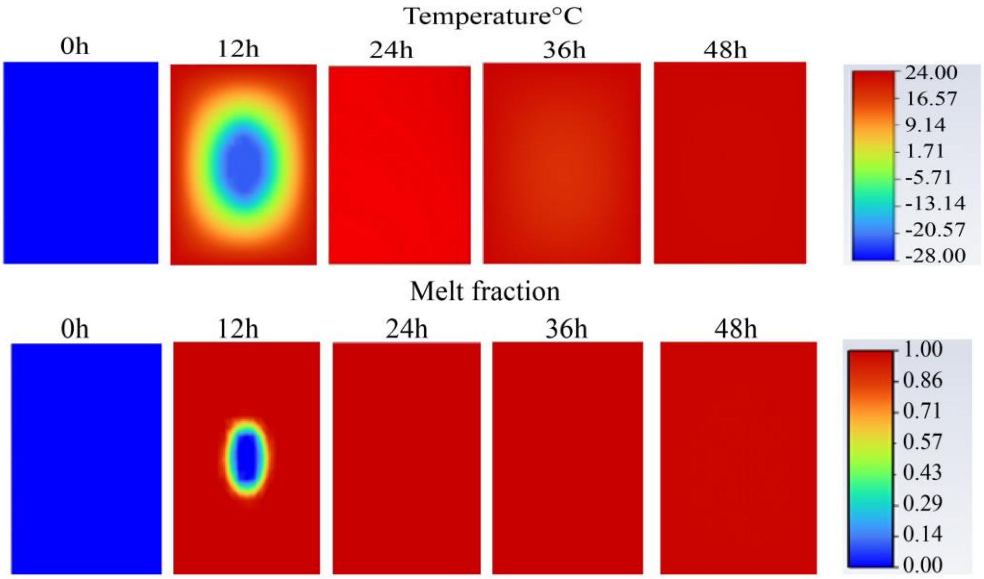


Fig. 18 Charts depicting the simulated temperature and melting at five distinct time points during the charging phase of the cold storage unit containing PCM NaCl-H_2O

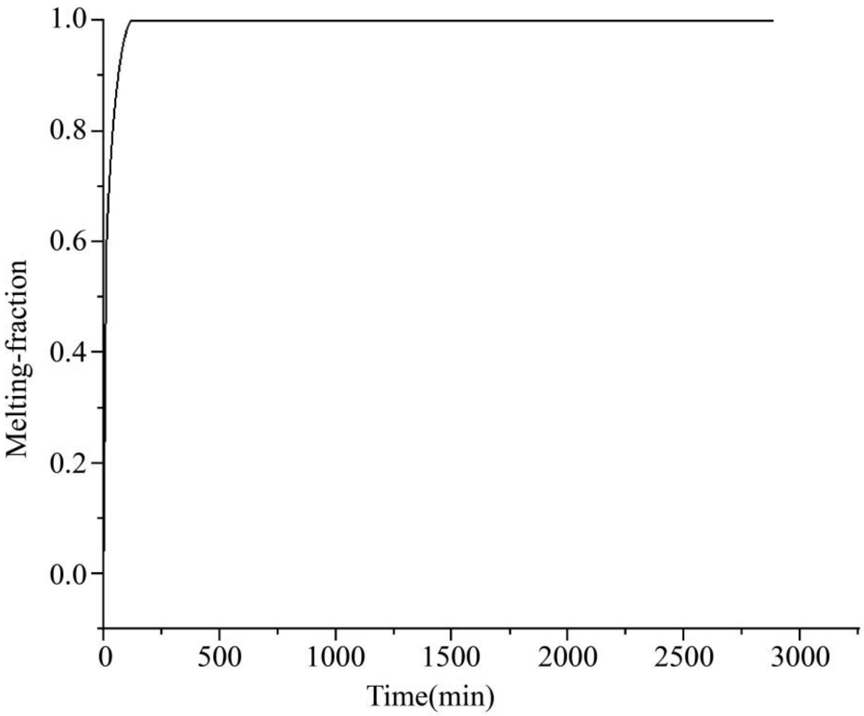


Fig. 19 Melting fraction discharging NaCl-H_2O

Fig. 16Figure 16 and 17 depict the temperature changes during the discharging process of distilled water, showing a rapid increase until a plateau at 0°C, indicating the phase change from solid to liquid. A secondary rise follows as all ice melts. As for ***Fig. 18***Figures 18***Fig. 19***, and 19 they pertain to a 23% NaCl-water solution. In this solution, the phase change material remains entirely liquid throughout the discharge, which is beneficial for efficiently absorbing thermal energy as a thermal buffer.

4.5. Discussions

The utilization of NaCl-water solutions as phase change materials presents a novel and innovative approach. While traditional PCMs have been extensively studied, the use of NaCl-water solutions offers unique advantages, particularly in cold storage applications. NaCl-water solutions exhibit sub-zero phase change behavior, enabling them to maintain lower temperatures compared to pure water or other conventional PCMs. This characteristic is crucial for enhancing the efficiency and effectiveness of cold storage systems, especially in regions with extreme climates or stringent temperature requirements. The study's thorough experiments offer detailed insights into NaCl-water solutions' thermal behavior during phase changes, facilitating the identification of optimal PCM concentrations and operational parameters for cold storage applications. Leveraging observed temperature plateaus enables the design of more stable and energy-efficient cold storage systems. The consistent data across NaCl concentrations allows for reliable modeling of cold storage systems, which is crucial for design and performance evaluation. Integrating experimental findings into computational models enables accurate prediction of temperature profiles and energy consumption, representing a significant advancement in PCM applications for cold storage.

The precise alignment between actual and simulated data for the charging temperature profiles of distilled water and the 23% salt-water solution, as depicted in Figure 12***Fig. 12*** to Figure 15***Fig. 15***, underscores the accuracy and reliability of the simulation approach. This validation of the simulation results enhances confidence in the predictive capabilities of the model, setting it apart from existing techniques that may lack such rigorous validation procedures. Understanding phase change kinetics in thermal energy storage systems is vital for optimization. The simulation model's detailed depiction, including the rapid temperature decrease, 0°C plateau indicating phase change, and subsequent freezing decline, provides valuable insights for system improvement. Accurately representing this plateau, often overlooked, ensures a more comprehensive understanding, aiding informed design decisions to enhance efficiency. Additionally, the inclusion of a separate graph on the melting fraction of distilled water provides further insights into freezing kinetics, contributing to the optimization of TES system design. This comprehensive analysis addresses efficiency concerns related to the extended freezing of the final liquid portions, enabling more effective system optimization and performance enhancement.

The accurate depiction of temperature changes during the discharging process of both distilled water and NaCl-H_2O PCM solutions, as illustrated in Figure***Fig. 16*** 16 to Figure***Fig. 19*** 19, highlights the precision of the simulation model. The result highlights the precision and significance of temperature changes, particularly in cold storage applications, in distilled water and NaCl-H_2O PCM solutions, emphasizing the prolonged plateau at 0°C during phase change and the equilibrium behavior of the discharging process, all contributing to optimizing thermal energy storage systems. Additionally, the specific focus on the 23% NaCl-water solution in Figures***Fig. 18*** 18, and 19 provides insights into the unique behavior of this PCM mixture. The observation that the PCM remains entirely liquid throughout the discharging process is particularly significant, as it indicates the potential for efficient thermal energy absorption as a thermal buffer. By highlighting such beneficial characteristics, the simulation approach adopted in this study facilitates informed decision-making in the design and optimization of TES systems, surpassing the limitations of existing techniques that may not adequately address the nuances of PCM behavior.

5. Conclusion

This study successfully explores the potential of NaCl-water solution-based PCMs in enhancing the thermal management of cold storage systems. The CFD model simulation was first validated by comparing obtained results against experimental data, showing high fidelity in capturing PCM thermal behavior during both the charging and discharging phases. The 23% NaCl-water solution emerges as the most promising PCM, aligning its melting temperature with the standard operating temperature of cold storage rooms at -18°C. This concentration demonstrates notable latent heat storage and release characteristics, ensuring stable temperatures during the thermal cycle. Furthermore, the study emphasizes the significance of considering phase change kinetics, revealing the substantial impact on the efficiency of cold storage systems. Prolonged temperature plateaus during phase transitions for the optimal PCM concentration suggest effective thermal buffering, mitigating risks of detrimental temperature fluctuations.

In summary, integrating a 23% NaCl-water PCM solution into cold thermal energy storage systems offers an efficient strategy for meeting stringent temperature requirements in frozen storage environments. The research implications extend to reducing energy consumption, enhancing operational stability, and potentially lowering the carbon footprint in cold storage operations. Future work should focus on scaling the PCM implementation and exploring its long-term durability and cost-effectiveness in commercial cold storage applications.

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