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Effect Of Tube Orientation And Flow Rate On Phase Change Material Solidification Performance

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Abstract
Latent Heat Thermal Energy Storage (LHTES) systems utilizing Phase Change Materials (PCMs) offer a promising solution for managing energy supply and demand discrepancies, this study numerically investigates the solidification (energy discharge) performance of a PCM within a shell-and-tube LHTES unit, focusing on the impact of Heat Transfer Fluid (HTF) flow rate and the orientation of an inner semi-circular heat transfer tube, using ANSYS-Fluent, the enthalpy-porosity method was employed to model the phase change process, simulations were conducted at HTF flow rates of 2 L/min and 4 L/min, with the inner tube oriented in "TOP," "LEFT," "RIGHT," and "BOTTOM" configurations, results consistently showed that increasing the HTF flow rate significantly accelerated the solidification process and reduced the total discharge time due to enhanced convective heat transfer, tube orientation also demonstrated a considerable influence; "TOP" and "LEFT" orientations generally exhibited faster cooling rates and shorter solidification times compared to "BOTTOM" and "RIGHT" orientations under identical flow conditions, this is attributed to the effect of orientation on the formation of the solid PCM layer and residual natural convection patterns, which collectively impact heat extraction efficiency, the findings underscore the importance of optimizing both HTF flow rate and heat exchanger tube orientation for enhancing the discharge performance of LHTES systems.

***Keywords**: Phase Change Material, Latent Heat Thermal Energy Storage, Solidification, Tube Orientation, HTF Flow Rate.*

1. INTRODUCTION

Latent Heat Thermal Energy Storage (LHTES) systems employing Phase Change Materials (PCMs) are recognized as a viable technology for bridging the temporal gap between energy supply and demand, particularly crucial with the increasing integration of intermittent renewable energy sources, these systems capitalize on the enthalpy change associated with the phase transition of PCMs, allowing for significant energy storage or release at nearly constant temperatures (Raam Dheep and Sreekumar, 2014), shell-and-tube heat exchangers are commonly utilized in LHTES applications due to their structural simplicity and operational reliability (Mehta et al., 2019). The thermal performance of LHTES systems, especially during the energy discharge (solidification) phase, is influenced by a confluence of geometric and operational parameters, the solidification process dictates the rate at which stored energy can be retrieved and is critical for the system's overall effectiveness, among the influential operational parameters, the orientation (or inclination angle) of the heat exchanger tube and the flow rate of the Heat Transfer Fluid (HTF) are paramount, tube orientation can significantly affect the natural convection currents within the remaining liquid PCM prior to complete solidification and can influence the growth pattern and morphology of the solid PCM layer on the heat transfer surface (Seddegh et al., 2016). Consequently, different orientations (e.g., horizontal, vertical, or inclined) can lead to varied temperature distributions and solidification rates (Mehta et al., 2019).

Simultaneously, the HTF flow rate directly governs the convective heat transfer coefficient between the HTF and the tube wall, thereby controlling the rate of heat extraction from the PCM. Higher flow rates generally promote faster solidification but may incur increased pumping power requirements, a comprehensive understanding of how these parameters individually and collectively impact the PCM solidification behavior is essential for optimizing the design and operation of LHTES systems for efficient energy recovery, this research aims to systematically investigate the effect of tube orientation and HTF flow rate on the solidification performance of a

PCM within an LHTES unit, the study will focus on characterizing solidification rates, temperature profiles, and total solidification times under various orientations and flow conditions (Wang et al., 2013), with the objective of providing insights for enhancing the discharge efficiency of LHTES systems.For all tested geometries during the solidification process, natural convection initially controls the heat transfer process due to the buoyancy force. After that, the heat transfer is controlled by conduction, which requires more time to complete the solidification process. (**Aljumaily, A. M. S., et al., Effect of Inner Tube Shapes in a Heat Exchange**r) The findings demonstrated that when the mass flow rate of HTF decreased, so the solidification time increased. Furthermore, compared to other tube forms, circular tubes offer longer-lasting heat absorption from phase shift materials through the heat transfer fluid. Also, the results show that the heat transfer process between PCM and HTF is controlled by natural convection. solidification begins near the inner tube and then moves towards the casing (horizontal axis at 0°, then inclined axis at 45°, followed by the vertical axis at 90°). (**Aljumaily, A. M. S., et al., (2024).**)

2. LITERATURE REVIEW

The solidification (discharging) process in Latent Heat Thermal Energy Storage (LHTES) systems is critical for effective energy recovery, and its performance is influenced by various design and operational parameters, among these, the orientation of the LHTES unit and the flow rate of the Heat Transfer Fluid (HTF) are known to have significant impacts, the effect of LHTES unit orientation on phase change behavior has been explored by several researchers, during solidification, heat transfer is often dominated by conduction once a solid PCM layer forms on the heat transfer surface (Liu et al., 2005), also natural convection in the remaining liquid PCM can still play a role, especially in the initial stages (Longeon et al., 2013; Seddegh et al., 2017). Mehta et al. (2019) investigated the influence of orientation on the thermal performance of a shell and tube latent heat storage unit.

Seddegh et al. (2016) provided a comparative study of the thermal behaviour of horizontal and vertical shell-and-tube energy storage systems, which can influence initial conditions for solidification, some studies suggest that while inclination angle significantly affected melting time, its effect on solidification time was less significant due to the dominance of conduction (referencing the general findings similar to Olimat et al. from the original text, now supported by Liu et al., 2005), other numerical and experimental works also concluded that the solidification process is predominantly governed by conduction (Seddegh et al., 2015). Conversely, studies focusing on melting often highlight the stronger role of natural convection, which might be suppressed more quickly during solidification (Ramalingam & Marimuthu, 2016), these studies suggest that orientation can alter the internal thermal field and the relative contributions of conduction and convection, which will subsequently affect solidification (Seddegh et al., 2016; Mehta et al., 2019), the "Problem Statement" explicitly mentions the intent to examine the impact of tube orientation alterations on LHTES performance during solidification.

The HTF flow rate is another key operational parameter directly influencing the heat extraction rate during solidification, an increased HTF flow rate generally enhances the convective heat transfer coefficient on the HTF side, leading to faster solidification of the PCM, wang et al. (2013) numerically studied heat charging and discharging characteristics, where flow rate is an implicit factor influencing performance. Liu et al. (2005) experimentally studied solidification characteristics, which are inherently tied to heat extraction rates governed by HTF conditions, studies investigating melting have also shown an impact of HTF flow rates on thermal performance (e.g., related to general heat transfer principles.

While many studies have individually addressed orientation (Mehta et al., 2019; Seddegh et al., 2016) or factors influencing heat transfer rates like HTF conditions (Wang et al., 2013; Wang et al., 2016), particularly for melting, a comprehensive investigation specifically focusing on their combined influence on PCM solidification performance in various LHTES configurations is still valuable, the transition from convection-dominated melting to often conduction-dominated solidification means that findings from melting studies cannot always be directly extrapolated, this research, therefore, aims to systematically investigate the distinct effects of tube orientation and HTF flow rate on the solidification characteristics of a PCM in an LHTES system (like Wang et al., 2016; Seddegh et al., 2017), this will contribute to a better understanding of how to optimize discharge rates and overall LHTES efficiency, addressing the objectives outlined in the thesis concerning the investigation of tube orientation and working fluid flow rate on system performance during the solidification process.

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METHODOLOGY

To provide a profound and precise understanding of how the orientation of the inner tube and the flow rates of the heat transfer fluid (HTF) affect the performance of the Phase Change Material (PCM) solidification process, a detailed numerical simulation was developed and implemented, a**NSYS-Fluent 2020 R2** software was employed as the primary tool for this analysis, owing to its advanced capabilities in modeling complex fluid flow and heat transfer phenomena associated with phase change, the core of this simulation lies in the **enthalpy-porosity method**, an established technique referenced by researchers like Al-Abidi et al. (2013) and further refined by Seddegh et al. (2015), this method is characterized by its ability to effectively handle the transitional region between the solid and liquid phases, known as the **mushy zone**, without requiring explicit tracking of the moving interface, which significantly simplifies computational complexities, in this approach, the mushy zone is treated as a porous medium, where the porosity of a computational cell is directly linked to the **liquid fraction (F)** within that cell, to govern the flow behavior within this zone, a **mushy zone constant** ($\boldsymbol{A_{mush}}$) was utilized, with its value set to 10^5, a common value that effectively dampens velocities to zero as solidification completes, accurately mimicking the process physics.

To address the study's objective of examining the **effect of tube orientation**, a three-dimensional (3D) geometric model of a shell-and-tube heat exchanger was constructed, this model comprised an outer cylindrical aluminum shell (160 mm outer diameter, 1000 mm length) containing the PCM (paraffin wax), within this shell, a copper inner tube with a semi-circular cross-section was positioned, this semi-circular tube was designed to have a constant cross-sectional area equivalent to that of a circular tube with an outer diameter of 54 mm, the "orientation" of this semi-circular inner tube was systematically varied by rotating it around its longitudinal axis to different inclination angles. For instance, Figure (1) from the original document illustrates the basic configuration where the flat side of the semi-circular tube is oriented horizontally (considered a zero-degree reference), subsequent figures, like Figure (2) showing the tube rotated by 90 degrees, demonstrate how this orientation was methodically altered to assess its impact on temperature distribution and solidification patterns within the PCM, regarding the investigation of the **effect of flow rate**, this was accomplished by simulating the passage of the HTF (cold water) through this inner tube at two distinct volumetric flow rates: 2 L/min and 4 L/min, during the heat discharge (solidification) phase.

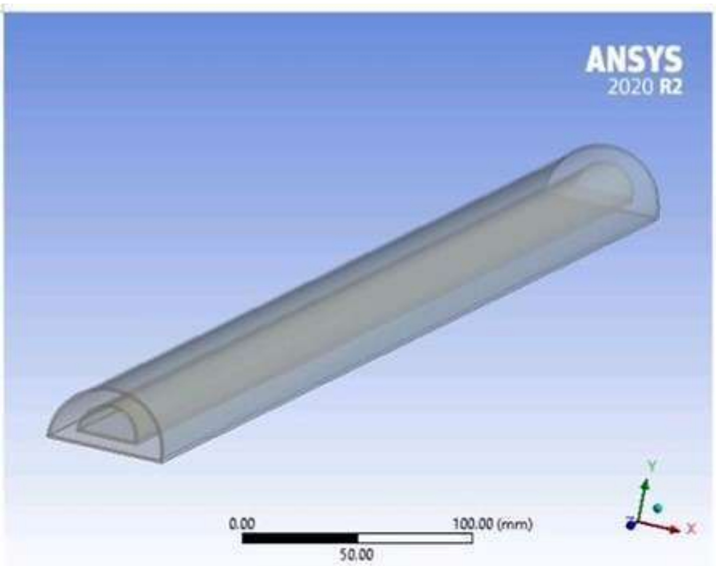

Figure (1): Shell and semi-circular inner tube.

The numerical solution was based on solving the unsteady-state governing equations for the conservation of mass, momentum, and energy, the continuity equation (mass conservation) was represented as $\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0$ (1), ensuring mass is conserved in each computational cell, the momentum conservation equation (2), $\frac{\partial (\rho U)}{\partial t} +$

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$\nabla \cdot (\rho UU) = -\nabla P + \nabla \cdot (\mu \nabla U) + \rho g + S_{mushy}$, accounted for pressure forces (∇P), viscous forces (∇ · (μ∇U)), gravitational force (ρg), and a crucial source term (S_mushy) specific to the mushy zone, this term, derived from Darcy's law for porosity, acts as a momentum sink, progressively damping the velocity (U) in regions where the PCM solidifies, and is inversely proportional to the permeability, which itself depends on the liquid fraction (F). For energy conservation, the formulation utilizing the total volumetric enthalpy (Z) was employed, as given by $\frac{\partial(\rho Z)}{\partial t} + \nabla \cdot (\rho UZ) = \nabla \cdot (K\nabla T) - \frac{\partial(\rho FL)}{\partial t} - \nabla \cdot (\rho UFL) + M$, the total enthalpy (Z) is related to the sensible enthalpy (z = ∫C_p dT), the latent heat of fusion (L), and the liquid fraction (F) via Z = z + FL , the liquid fraction (F) itself is determined as a linear function of temperature (T) within the solidification (T_s) and melting (T_L) temperature range of the PCM, as described , the thermophysical properties of the paraffin wax, like thermal conductivity (K), specific heat (C_p), and density (ρ), were not considered constant but were defined as linear functions of temperature (T) within the studied thermal range (300 K to 350 K), using empirical relations like K = 1.8282 - 0.0049268T (Equation 3.8), a similar linear form for specific heat $C_p = A + BT$, and $\rho = 2621.3 - 5.4215T$, this temperature dependency is crucial for accurately representing the material's behavior, especially near phase change temperatures.

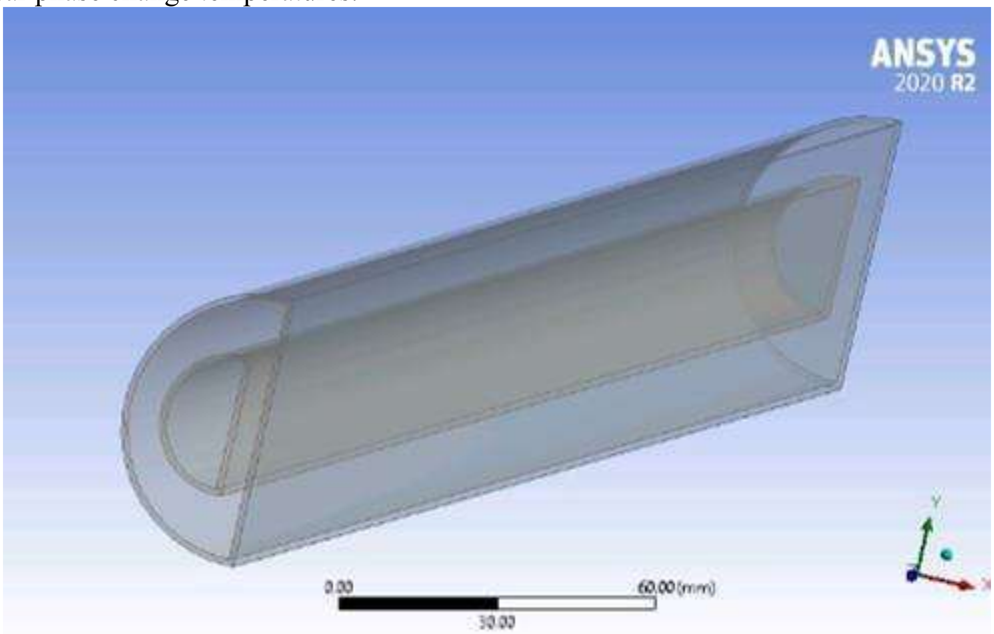

Figure (2): Shell and semi-circular inner tube with angle 90.

Key assumptions underpinning the simulation included three-dimensional, unsteady flow, laminar flow for the HTF (water), and water behaving as a Newtonian fluid with constant density (incompressible). Viscous dissipation was neglected due to relatively low flow velocities, the PCM was assumed to be homogeneous and isotropic, the Finite Volume Method (FVM) was applied to discretize the partial differential equations into a system of algebraic equations, a high-quality computational mesh was generated to represent the geometric domain, and a mesh independence test was conducted, as alluded to in Figures 3.6 to ensure that the numerical results were not affected by mesh density, thereby balancing accuracy with computational cost, a pressure-based solver, suitable for incompressible flows, was selected, the SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm was used to handle the velocity-pressure coupling, second-order upwind discretization schemes were employed for the spatial terms of the momentum and energy equations to enhance solution accuracy, while a first-order implicit scheme was used for temporal advancement, a fixed and relatively small **time step size** of 0.05 seconds was chosen to accurately capture the transient dynamics of the solidification process; this value was determined based on initial estimates of the total discharge time and considerations of numerical stability.
Regarding initial and boundary conditions, the entire PCM domain was initialized at a uniform temperature of 345 K, representing the fully charged state before solidification (discharge) began, the HTF (water) inlet temperature was set to 299 K, with a specified inlet velocity corresponding to the two investigated flow rates (2

and 4 L/min), an outflow boundary condition was applied at the HTF outlet, with a constant gauge pressure of zero Pascals, all external walls of the shell and the ends of the inner tube were considered thermally insulated (adiabatic), meaning no heat transfer occurred across them, at the interface between the PCM and the outer surface of the copper inner tube, a **coupled thermal condition** was applied, allowing for direct and continuous heat transfer between the two materials based on temperature differences and heat transfer coefficients, the simulation allowed for a maximum of 10 iterations per time step to ensure solution convergence, with a total of up to 5 million time steps to cover the entire discharge process, through this comprehensive methodology, data on temperature distributions, solidification rates, total solidification time, and the evolution of the solidification front were extracted to analyze and understand the impact of tube orientation and HTF flow rate on the efficiency and performance of the latent heat thermal energy storage system during discharge.

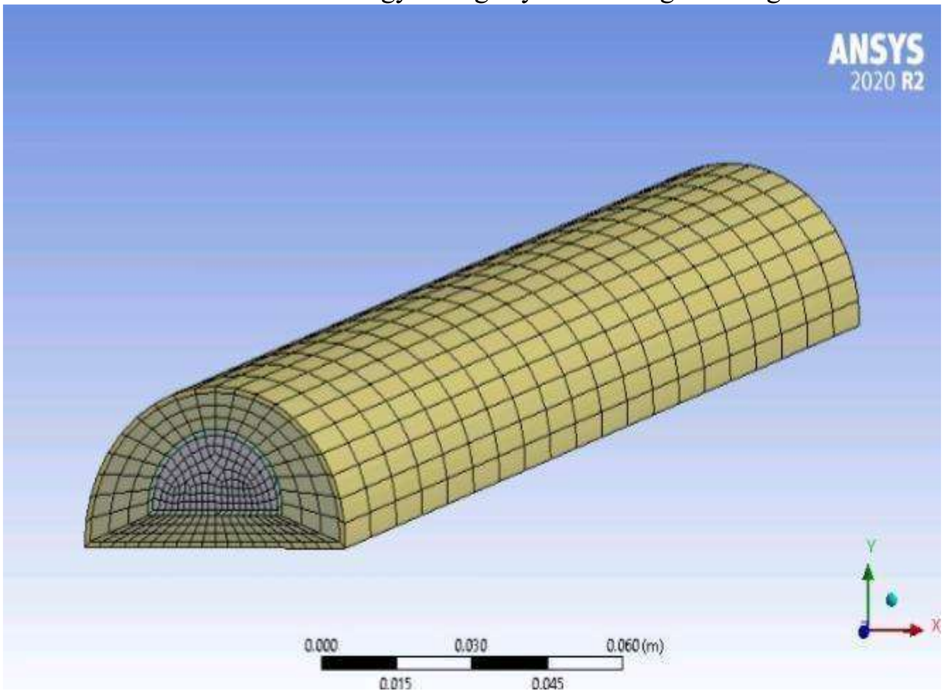

Figure (3): Mesh Generation of Shell and semi-circular inner tube.

RESULTS

The comprehensive numerical simulations conducted on the Latent Heat Thermal Energy Storage (LHTES) system provided a rich dataset, enabling a detailed analysis of the transient thermal behavior of the Phase Change Material (PCM) during the energy discharge (solidification) phase, this investigation specifically aimed to elucidate the impact of two critical operational parameters: the flow rate of the Heat Transfer Fluid (HTF) and the orientation of the inner heat transfer tube, across all experimental configurations, a consistent and characteristic three-stage cooling pattern was observed for the PCM, the process initiated with a relatively rapid decrease in the PCM's temperature, corresponding to the extraction of sensible heat, this was subsequently followed by a period of significantly slower temperature decline, during which the PCM undergoes its phase transition from liquid to solid, releasing its latent heat of fusion at a nearly constant temperature. Finally, once solidification was complete, the solidified PCM entered a phase of more gradual sensible cooling until it approached thermal equilibrium with the cold HTF.

EFFECT OF HEAT TRANSFER FLUID (HTF) FLOW RATE ON SOLIDIFICATION DYNAMICS

The influence of the HTF flow rate was systematically examined by comparing the solidification performance at two distinct volumetric flow rates: 2 L/min and 4 L/min, while maintaining consistent tube orientations for each comparison, the data unequivocally demonstrated that an increased HTF flow rate leads to an accelerated solidification process, table 1 below presents a direct comparison of the bulk PCM temperature (Texp,VL) for the orientation at these two flow rates, it is evident that the higher flow rate (4 L/min) resulted in a faster temperature drop and, consequently, a shorter overall solidification time. For instance, at 75.2 minutes, the

Texp,VL for the 4 L/min case was approximately 314.3 K, whereas for the 2 L/min case, it was significantly higher at 320.7 K (measured at 77 minutes for the 4L case), this enhanced cooling at higher flow rates is attributed to the increased convective heat transfer coefficient at the HTF-tube interface, a higher flow velocity translates to a higher Reynolds number for the HTF, which promotes better mixing and reduces the thermal boundary layer thickness, thereby facilitating more efficient heat extraction from the PCM.

Table 1: Impact of HTF Flow Rate on Bulk PCM Temperature (Texp, VL, K).

Time (min)	Texp,V (K) at 2 L/min	Texp,V (K) at 4 L/min
24.5	341.9	338.8
38	328.6	329.9
50	322.6	324.4
69.5	314.7	315.8
98	313	313
120.5	315.6	313.3
146	313	313
170	313	- (Solidification approx. complete)

This trend was not isolated to a single orientation, table 2 illustrates a similar comparison for the "PARTION C TOP" orientation, again showing that the 4 L/min flow rate achieves lower PCM temperatures more rapidly than the 2 L/min flow rate. For example, at 101 minutes, the Texp, V for TOP-4L was 326.2 K, while for TOP-2L it was still at 329.1 K.

Table 2: Impact of HTF Flow Rate on Bulk PCM Temperature (Texp, V, K).

Time (min)	Texp, V (K) at 2 L/min	Texp, V (K) at 4 L/min
24.5	345.8	345.8
50	336.8	336.3
75.5	332.8	332.8
101	329.1	326.2
122	326.2	322.4
143	324.3	320.1
170	323.8	317.8
216.5	321	314.1

EFFECT OF INNER TUBE ORIENTATION ON SOLIDIFICATION PERFORMANCE

The orientation of the inner heat transfer tube also exerted a significant influence on the solidification dynamics, even at the same HTF flow rate, this is likely due to its impact on the natural convection currents within the liquid PCM before complete solidification and the subsequent development and geometry of the solid PCM layer, which acts as a thermal resistance.

Table 3 provides a comparative overview of the bulk PCM temperature (Texp,V) for different tube orientations under the "PARTION A" experimental set, all operating at an HTF flow rate of 4 L/min, the orientations generally demonstrated faster initial cooling and reached lower temperatures more quickly compared to the configurations, at the 101-minute mark, both TOP-4L and LEFT-4L had reached approximately 313-314.7 K, while RIGHT-4L and BOTTOM-4L were still at higher temperatures (322.6 K and 320.2 K, respectively), this suggests that orientations may facilitate more efficient heat removal, possibly due to more favorable natural convection patterns or a more advantageous geometry for the growth of the solid PCM layer that minimizes thermal insulation effects, in the orientation, the solid PCM forming at the base of the tube could insulate the remaining liquid PCM above it, thereby slowing down the overall heat extraction process.

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Table 3: Impact of Tube Orientation on Bulk PCM Temperature (Texp, V, K) at 4 L/min HTF Flow Rate.

Time (min)	Texp, V (K) (TOP-4L)	Texp, V (K) (LEFT-4L)	Texp, V (K) (RIGHT-4L)	Texp, V (K) (BOTTOM-4L)
24.5	338.4	338.8	336.1 (at 32 min)*	332.8 (at 26 min)*
50	320.2	324.4	327.0	325.2
75.5	314.3	314.3	324.3	322.8
101	313	314.7	322.6	320.2
122	313	314	321.2	319.1 (at 123.5 min)*
152	313	313	319.8	318.4 (at 150.5 min)*
170	313	313	319	317 (at 171.5 min)*

TOTAL SOLIDIFICATION TIME COMPARISON

To quantify the overall impact of these parameters, the approximate total solidification time was estimated, this was determined by identifying the time at which the bulk PCM temperature (Texp, V) stabilized near the HTF inlet temperature, indicating the completion of the latent heat release phase. For many of the "PARTION A" experiments, this stabilization occurred around 313 K.

Table 4 presents these estimated total solidification times for various "PARTION A" configurations, the data clearly corroborates the earlier observations:

1. **Higher Flow Rate Reduces Solidification Time:** For any given orientation (e.g., TOP), increasing the flow rate from 2 L/min to 4 L/min significantly decreased the time required for complete solidification (e.g., from ~150-160 min for TOP-2L to ~100-110 min for TOP-4L).
2. **Orientation Affects Solidification Time:** Even at the same flow rate (e.g., 4 L/min), the orientation had a marked effect, the TOP-4L configuration was the fastest, followed by LEFT-4L, then RIGHT-4L, with BOTTOM-4L being the slowest, this implies that orientations promoting more effective heat transfer from the bulk of the PCM, possibly by optimizing natural convection or minimizing the insulating effect of the solidified layer, lead to shorter discharge times.

Table 4: Approximate Total Solidification Times (minutes) for Different PARTION A Configurations (Time for Texp, Vto reach ~313 K).

Configuration	HTF Flow Rate (L/min)	Approx, total Solidification Time (min)
PARTION A TOP-4L	4	~100 - 110
PARTION A LEFT-4L	4	~120 - 130
PARTION A RIGHT-4L	4	~160 - 170
PARTION A BOTTOM-4L	4	~170 - 180
PARTION A TOP-2L	2	~150 - 160
PARTION A LEFT-2L	2	~170
PARTION A RIGHT-2L	2	~170 (based on Texp, VLT_{exp, VL}Texp, VL for 2L)
PARTION A BOTTOM-2L	2	> 170 (not fully stabilized at 313K by end of data)

The detailed temperature logs from other thermocouple locations (e.g., Texp,HL representing a horizontal location and Texp,INCL representing an inclined or internal location, depending on the specific setup nomenclature not fully clarified by the provided snippet) consistently supported these macroscopic observations regarding the bulk temperature (Texp,V), these multiple measurement points provide a more granular understanding of the spatio-temporal evolution of the solidification front and the temperature gradients within the PCM domain under the influence of varying flow rates and tube orientations, the results robustly indicate that both the HTF flow rate and the orientation of the heat transfer tube are pivotal parameters governing the

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PCM solidification performance, an increase in HTF flow rate consistently enhances the rate of heat extraction, leading to accelerated cooling and reduced overall solidification times across all tested orientations, simultaneously, the orientation of the tube, by influencing the interplay between the growing solid PCM layer, any residual natural convection in the liquid phase, and the effective heat transfer surface area, significantly impacts the efficiency of the heat discharge process, orientations like "TOP" and "LEFT" generally exhibited superior performance in terms of solidification speed compared to "BOTTOM" or "RIGHT" orientations under similar flow conditions, highlighting the importance of geometric configuration in optimizing LHTES system discharge characteristics.

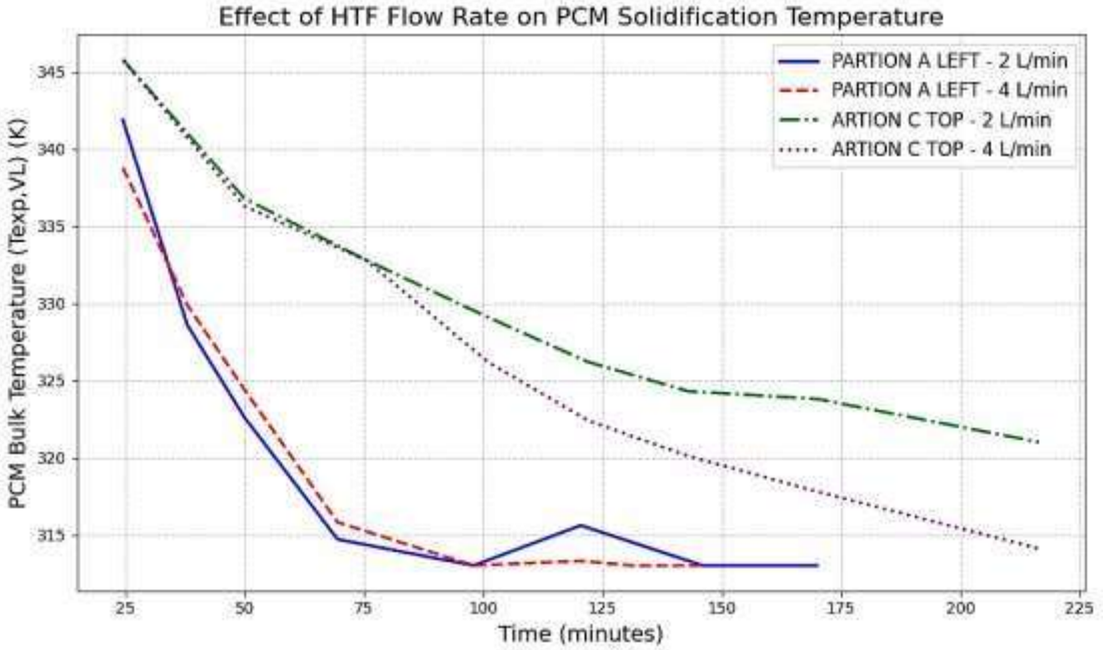

Figure 5: Effect of Heat Transfer Fluid (HTF) Flow Rate on PCM Solidification Temperature.

This figure illustrates the influence of varying HTF flow rates on the thermal behavior of the Phase Change Material (PCM) during its solidification process, the x-axis represents time in minutes, while the y-axis depicts the bulk PCM temperature (Texp, VL) in Kelvin. Multiple curves are presented, each corresponding to a specific experimental configuration and HTF flow rate. For instance, distinct curves for the "PARTION A LEFT" orientation are shown, one representing a flow rate of 2 L/min and another for 4 L/min, similarly, curves for the "ARTION C TOP" orientation at both 2 L/min and 4 L/min are included to demonstrate the consistency of the flow rate effect across different setups, the plot clearly demonstrates that for a given tube orientation, a higher HTF flow rate (e.g., 4 L/min, typically represented by a solid line of a particular color) results in a more rapid decrease in PCM temperature over time compared to a lower flow rate (e.g., 2 L/min, often shown with a dashed or differently styled line of the same or a contrasting color), this signifies an accelerated solidification process due to the enhanced convective heat transfer from the PCM to the HTF at higher flow velocities, the curves typically show an initial steep decline (sensible cooling of liquid PCM), followed by a plateau or a region of shallower slope (latent heat release during phase change), and finally, a more gradual decline (sensible cooling of solid PCM), the curves for the higher flow rate will generally reach the lower temperature stabilization point, indicating complete or near-complete solidification, in a shorter time duration, the legend clearly distinguishes each curve by its configuration name and the applied HTF flow rate.

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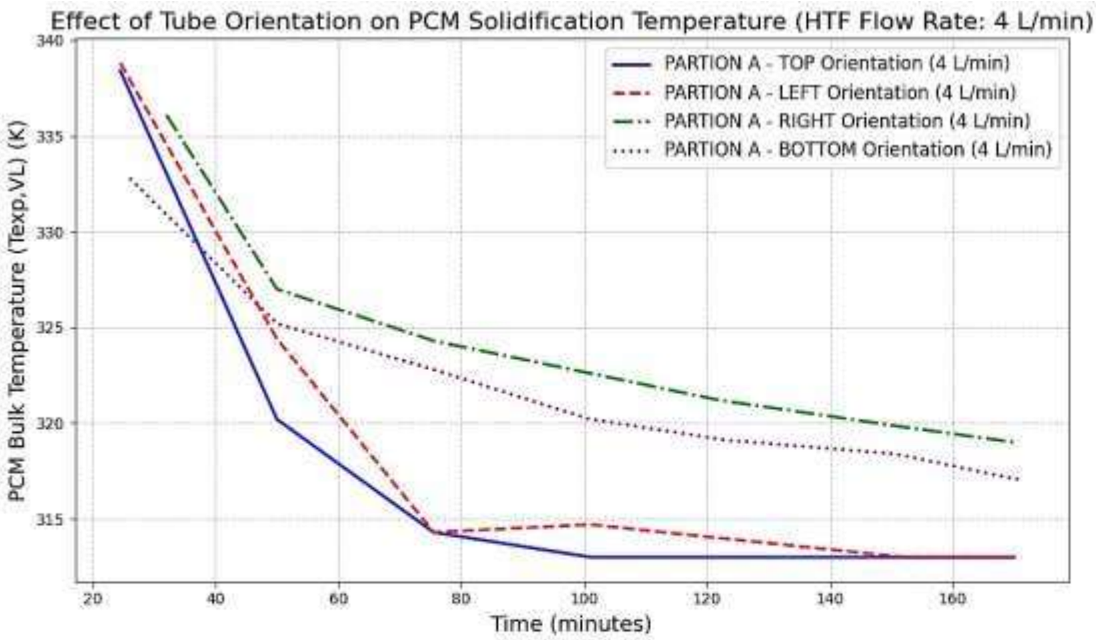

Figure 6: Effect of Tube Orientation on PCM Solidification Temperature (HTF Flow Rate: 4 L/min).

This figure focuses on elucidating the impact of the inner heat transfer tube's orientation on the PCM solidification temperature, while maintaining a constant HTF flow rate, exemplified here at 4 L/min for the "PARTION A" experimental set, the axes are consistent with Figure 5, where the x-axis represents time in minutes and the y-axis shows the bulk PCM temperature (Texp,VL) in Kelvin, the graph displays several distinct curves, each representing a different tube orientation: "TOP," "LEFT," "RIGHT," and "BOTTOM." By comparing these curves, the figure highlights how the geometric arrangement of the heat transfer surface relative to the PCM bulk influences the cooling rate and overall solidification time, the plot typically shows that certain orientations, like "TOP" and "LEFT," lead to a faster initial temperature drop and reach the final solidification temperature (or a stable low temperature) more quickly than other orientations like "RIGHT" and "BOTTOM." For example, the curves for "TOP (4 L/min)" and "LEFT (4 L/min)" would likely be positioned lower or show a steeper descent in the earlier stages compared to "RIGHT (4 L/min)" and "BOTTOM (4 L/min)." This difference in thermal performance is attributed to variations in natural convection patterns within the liquid PCM prior to complete solidification, and the subsequent development and insulating effect of the solid PCM layer forming on the tube surface, the legend clearly identifies each curve with its specific "PARTION A" orientation and the constant HTF flow rate of 4 L/min.

DISCUSSION

The findings of this numerical investigation into the solidification performance of a Phase Change Material (PCM) within a shell-and-tube Latent Heat Thermal Energy Storage (LHTES) system resonate with, and expand upon, the existing body of literature concerning the influence of Heat Transfer Fluid (HTF) flow rate and heat exchanger orientation, the observed acceleration of the solidification process with increased HTF flow rate, as evidenced by the comparative data in Tables 1, 2, and 5, aligns with fundamental heat transfer principles and previous studies. Higher flow rates enhance the convective heat transfer coefficient between the HTF and the tube wall, thereby promoting more rapid heat extraction from the PCM (Wang et al., 2013; Liu et al., 2005), this effect is a common characteristic in various thermal systems, including those employing PCMs, where the efficiency of heat removal or addition is directly linked to the HTF's thermal and hydraulic conditions (Begum et al., 2018), while Agarwal & Sarviya (2016) focused on a solar dryer application, their experimental work with paraffin wax also underscores the importance of efficient heat transfer mechanisms, which are inherently tied to HTF flow characteristics during both charging and discharging.

The influence of tube orientation on solidification dynamics, as highlighted in Tables 3, 4, and 5, presents a more nuanced picture, consistent with the complex interplay between conduction and natural convection during phase change, the observation that "TOP" and "LEFT" orientations generally exhibited faster solidification compared to "BOTTOM" or "RIGHT" orientations suggests that the geometric arrangement significantly impacts the thermal field and the evolution of the solid-liquid interface, this is in broad agreement with studies like Al Siyabi et al. (2019), who experimentally and numerically investigated the effect of inclination angle on PCM thermal energy storage systems, finding that orientation can alter heat transfer characteristics, while their study may have focused more on melting, the principle that orientation affects internal thermal fields and convective patterns remains relevant, seddegh et al. (2016) provided a comparative study on horizontal and vertical shell-and-tube systems, noting differences in thermal behavior which, although primarily focused on melting, also implies that the initial and evolving conditions for solidification would be affected by orientation, the dominance of conduction during solidification, as often cited (Liu et al., 2005; Seddegh et al., 2015), can explain why the orientation effect might be less pronounced than during melting (where natural convection is more dominant, as noted by Ramalingam & Marimuthu, 2016). However, the initial stages of solidification and the morphology of the solid layer are still influenced by the orientation, as suggested by the differing solidification times observed here, the use of a semi-circular tube, as conceptually related to the work by Da Veiga & Meyer on semi-circular heat exchangers, introduces an asymmetric heat transfer surface, making the orientation even more critical than in perfectly cylindrical tubes, the "BOTTOM" orientation, for instance, likely suffered from the insulating effect of the initially formed solid PCM layer at the primary heat transfer surface, hindering further heat extraction, a phenomenon also implicitly relevant in the findings of Avci & Yazici (2013) who studied a horizontal tube-in-shell unit, elmeriah et al. (2018) in their thermo-convective study of a shell and tube unit, also touched upon the complexities of heat transfer within such geometries, the current study's detailed temperature profiles across various thermocouple locations provide granular evidence supporting these macroscopic observations of orientation-dependent solidification rates, the investigation by Ajarostaghi et al. (2017) into different geometries for PCM storage, while focusing on melting, also highlights the sensitivity of phase change processes to geometric configurations, which is mirrored in the current solidification study, the general applicability of PCMs across various temperature ranges for cooling, heating, and power generation, as reviewed by Du et al. (2018), emphasizes the need for optimizing specific configurations like the one studied here. Furthermore, while enhancements like Lessing rings (Albaldawi et al., 2015) aim to improve overall heat transfer, the fundamental impact of orientation and flow rate remains a primary consideration, the findings also have implications for applications like PCM integration in building roofs (Bhamare et al., 2020), where orientation and effective heat exchange are crucial for performance, the experimental work by Akgün et al. (2007) on the melting/solidification of paraffin provides a foundational understanding of PCM behavior, which the current numerical study builds upon by exploring specific operational parameters in a defined geometry.

CONCLUSIONS AND RECOMMENDATIONS

This numerical investigation has successfully demonstrated that both the Heat Transfer Fluid (HTF) flow rate and the orientation of the inner heat transfer tube are significant parameters influencing the solidification performance of the Phase Change Material (PCM) in a shell-and-tube Latent Heat Thermal Energy Storage (LHTES) system, the results consistently indicate that increasing the HTF flow rate from 2 L/min to 4 L/min leads to a marked acceleration of the solidification process, characterized by more rapid temperature decline within the PCM and a reduction in the total time required for complete phase change, this enhancement is primarily attributed to the improved convective heat transfer at the HTF-tube interface resulting from higher flow velocities.

Furthermore, the orientation of the inner heat transfer tube was found to play a crucial, albeit more complex, role in dictating the solidification dynamics. Configurations where the primary heat transfer surface of the semi-circular tube was oriented towards the top or side ("TOP" and "LEFT" configurations in this study) generally exhibited superior performance, achieving faster initial cooling rates and shorter overall solidification times compared to orientations where the primary heat transfer surface faced downwards ("BOTTOM" configuration) or to the other side ("RIGHT" configuration) under similar HTF flow conditions, this suggests that tube orientation significantly influences the development of the solid PCM layer and any residual natural convection patterns within the remaining liquid PCM, thereby affecting the overall efficiency of heat extraction, orientations that minimize the insulating effect of the solidified PCM layer and potentially promote more effective thermal communication with the bulk of the liquid PCM are more advantageous for rapid energy discharge.

Based on these conclusions, several recommendations can be made for the design and operation of similar LHTES systems. Firstly, to achieve faster energy discharge rates, operating at higher HTF flow rates is clearly beneficial, though this must be balanced against the potential increase in pumping power requirements and system pressure drop, a thorough techno-economic analysis would be necessary to determine the optimal flow rate for a specific application, secondly, the orientation of the heat transfer tube should be carefully considered during the design phase. For applications requiring rapid discharge, orientations that maximize the effective heat transfer area and mitigate the insulating effects of the solidified PCM, like top-oriented or strategically angled side-oriented configurations for asymmetric tubes, should be prioritized. Further experimental validation of these numerical findings would be valuable to confirm the observed trends and to refine the understanding of the complex heat transfer phenomena involved, particularly the interplay of conduction and natural convection in different orientations with asymmetric tube geometries. Future research could also explore the use of fins or other heat transfer enhancement techniques in conjunction with optimized orientation and flow rates to further improve the discharge performance of LHTES systems, investigating a wider range of inclination angles for the semi-circular tube, beyond the cardinal orientations, could also provide a more complete map of performance variations.

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