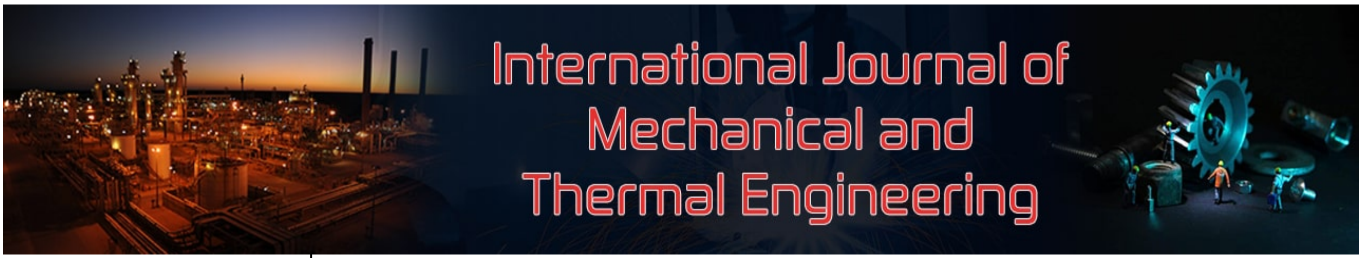

E-ISSN: 2707-8051
P-ISSN: 2707-8043
IJMTE 202; 6(2): 12-19
www.mechanicaljournals.com/ijmte
Received: 12-05-2025
Accepted: 13-06-2025

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The effect of temperature variation of water on melting of PCM inside latent heat energy storage

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DOI: https://www.doi.org/10.22271/27078043.2025.v6.i2a.91

Abstract
This study presents a numerical investigation into the melting dynamics of a Phase Change Material (PCM) within a shell-and-tube Latent Heat Thermal Energy Storage (LHTES) system, the primary objective was to elucidate the effect of varying the rate of temperature change, controlled via two key operational parameters: the Heat Transfer Fluid (HTF) inlet temperature and its volumetric flow rate, a three-dimensional computational fluid dynamics (CFD) model was developed and solved using the enthalpy-porosity method in ANSYS-Fluent, the results demonstrate that both parameters significantly influence the energy charging (melting) performance, increasing the HTF flow rate from 2 L/min to 4 L/min accelerated the melting process by enhancing the convective heat transfer coefficient at the fluid-wall interface. However, the HTF inlet temperature was identified as the dominant factor, elevating the HTF temperature from 343 K to 353 K drastically reduced the total melting time from approximately 150 minutes to 110 minutes under a 4 L/min flow rate, this profound acceleration is attributed to the combined effect of a larger thermal gradient and, more critically, the intensification of buoyancy-driven natural convection currents within the molten PCM, the study concludes that for optimizing the melting rate, controlling the HTF inlet temperature is the most effective strategy.

Keywords: Latent heat thermal energy storage (LHTES), phase change material (PCM), melting dynamics, natural convection, heat transfer enhancement

1. Introduction
The imperative for sustainable energy solutions has positioned Latent Heat Thermal Energy Storage (LHTES) as a critical enabling technology, essential for mitigating the intermittency of renewable sources and optimizing industrial waste heat recovery, by harnessing the high energy density associated with the solid-liquid phase transition of Phase Change Materials (PCMs), LHTES systems can store and release vast amounts of thermal energy at a nearly constant temperature, providing a robust buffer between energy supply and demand (Akgün *et al.*, 2007) [3], the shell-and-tube heat exchanger configuration remains a preferred design for these systems, valued for its structural integrity, scalability, and established manufacturing protocols (Avci & Yazici, 2013) [7]. 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 Exchanger) 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) [6]. The efficacy of an LHTES unit, particularly during the crucial energy charging (melting) cycle, is fundamentally dictated by the rate at which heat is assimilated by the PCM, this process is governed by the imposed rate of temperature change at the heat transfer boundary, a parameter that is not abstract but is directly manipulated through two primary operational variables: the inlet temperature of the Heat Transfer Fluid (HTF) and its mass flow rate (Begum *et al.*, 2018) [8], the HTF inlet temperature establishes the thermal potential (ΔT) that drives heat across the tube wall, serving as the primary thermodynamic force for melting. Simultaneously, the HTF flow rate

dictates the fluid-side thermal resistance by controlling the convective heat transfer coefficient; a higher flow rate minimizes this resistance, ensuring that the tube wall temperature remains elevated and promoting rapid heat delivery (Agarwal & Sarviya, 2016) [1].

The physics of melting within a confined geometry is profoundly influenced by buoyancy-induced natural convection, as the PCM layer adjacent to the heated surface melts, it undergoes a density reduction, causing the warmer, lighter liquid to ascend, this initiates a powerful thermosyphonic flow, where the molten PCM circulates, transporting thermal energy far more effectively than pure conduction would allow, this phenomenon transforms the melting front from a uniform, concentric shape into a highly complex, time-dependent morphology (Ajarostaghi *et al*., 2017) [2], understanding how the HTF's temperature and flow rate—the key drivers of the "rate of temperature change"—modulate the onset, intensity, and structure of these convective currents is therefore the central challenge in optimizing the charging performance of LHTES systems, this research undertakes a systematic investigation into this coupling, aiming to elucidate the intricate relationship between HTF operational parameters and the resulting melting dynamics, with the ultimate goal of formulating strategies for accelerated energy storage.

2. Literature Review

The scientific literature on Latent Heat Thermal Energy Storage (LHTES) extensively documents that the melting process is fundamentally distinct from and more complex than solidification, while solidification is frequently a conduction-dominated process, melting is characterized by the powerful influence of natural convection, which becomes the dominant heat transfer mechanism once a liquid phase is established, this convective transport, driven by buoyancy forces within the molten PCM, is responsible for the characteristically non-uniform melting patterns and significantly enhanced heat transfer rates observed in practice (Al-Abidi *et al*., 2013; Seddegh *et al*., 2017) [26, 21], the performance of the melting cycle is thus critically sensitive to operational parameters that influence the intensity of these convective flows.

The most direct method to vary the rate of heat input is by adjusting the HTF inlet temperature, a higher HTF temperature creates a larger temperature gradient between the heat source and the PCM's melting point, which has two profound effects. Firstly, it increases the initial conductive heat flux, accelerating the formation of the initial liquid layer. Secondly, and more critically, it results in a hotter molten PCM, leading to larger density differences and thus stronger buoyancy forces, this intensification of the natural convection loop is the primary reason for the dramatic reduction in total melting time reported across numerous studies. For instance, the experimental and numerical work by Seddegh *et al*. (2015) [18] explicitly demonstrated that increasing the heating fluid temperature from 70°C to 90°C resulted in a significant acceleration of the melting process in a shell-and-tube unit, this finding is consistent with a broad consensus in the field: the charging rate of an LHTES system is highly sensitive to the imposed boundary temperature.

The mass flow rate of the HTF, often quantified by the Reynolds number (Re), governs the external thermal resistance between the fluid and the heat exchanger wall. An increase in the flow rate enhances turbulence and improves the convective heat transfer coefficient (h), thereby reducing the temperature drop from the bulk fluid to the tube wall, this ensures that the PCM is exposed to a more consistently high temperature, facilitating faster melting. Wang *et al*. (2013) [24] numerically showed that system performance during charging is intrinsically linked to HTF conditions. However, the influence of the flow rate is subject to the principle of diminishing returns, as the flow rate becomes sufficiently high, the external thermal resistance becomes negligible compared to the internal thermal resistance on the PCM side (dominated by natural convection and conduction), at this juncture, the melting process becomes the rate-limiting step, and further increases in HTF flow rate yield only marginal improvements in melting time, albeit at the cost of significantly higher pumping power (Ramalingam & Marimuthu, 2016) [16].

While the individual impacts of HTF temperature and flow rate are well-established, their interactive and synergistic effects on the complex, evolving flow field during melting are a more advanced area of inquiry, the interplay between a high ΔT (from HTF temperature) and a high h (from HTF flow rate) determines the true "rate of temperature change" experienced by the PCM and shapes the evolution of the melt front. For example, a system operating at a moderate HTF temperature but a very high flow rate might perform differently than one at a very high HTF temperature but a low flow rate, a comprehensive investigation that decouples and compares these effects is necessary for true system optimization, this research addresses this gap by systematically mapping the melting performance across a matrix of HTF temperatures and flow rates, providing a detailed characterization of how these controllable parameters collectively govern the charging dynamics of an LHTES system, table 1 compares the approaches and findings of relevant studies focusing on the operational parameters that influence PCM melting

Table 1: Comparative of Methodologies in Key Studies.

Study (Author, Year)	Methodology	PCM Configuration	Investigated Parameters	Key Finding/Contribution on Melting Dynamics
Seddegh *et al*. (2015, 2017) [21]	Experimental & Numerical (CFD)	Horizontal & Vertical Shell-and-Tube	HTF Temperature, Orientation	Demonstrated that higher HTF temperatures drastically reduce melting time by intensifying natural convection, the melt front shape is highly asymmetric in horizontal units due to the upward movement of the molten plume.
Al-Abidi *et al*. (2013) [26]	Numerical (CFD)	Triplex Tube Heat Exchanger with Fins	HTF Temperature, HTF Flow Rate (Re)	Confirmed that increasing both HTF temperature and Reynolds number accelerates melting. Found that fins significantly enhance heat transfer by increasing the surface area, working in tandem with the HTF conditions.
Wang *et al*.	Numerical (CFD)	Shell-and-Tube	Charging/Discharging Cycles (implicitly	Provided validated numerical models for predicting LHTES performance. Showed that charging time is highly sensitive to the

(2013, 2016) [24]			includes HTF conditions)	boundary conditions set by the HTF.
Ramalingam & Marimuthu (2016) [16]	Experimental & Numerical	Horizontal Shell-and-Tube	HTF Flow Rate (Re), HTF Temperature	Identified the effect of "diminishing returns" for HTF flow rate. Above a certain Reynolds number, the internal thermal resistance of the PCM becomes the bottleneck, and increasing flow rate offers minimal benefit.
Longeon *et al.* (2013) [12]	Experimental	Shell-and-Tube	Heating Power (related to HTF Temp.)	Provided detailed experimental visualization and data on the dominance of natural convection. Characterized the different phases of melting: initial conduction, convection development, and final convection dominance.
Esapu *et al.* (2018)	Experimental	Vertical Shell-and-Tube	HTF Temperature, HTF Flow Rate	Systematically investigated the combined effect. Concluded that HTF temperature has a more pronounced effect on reducing melting time than the HTF flow rate, especially once the flow is in the turbulent regime.

3. Methodology

To conduct a rigorous and deeply analytical investigation into how the rate of temperature change governs the melting dynamics of a Phase Change Material (PCM), a comprehensive numerical model was developed and implemented, the entire simulation framework was built within the commercial Computational Fluid Dynamics (CFD) software ANSYS-Fluent 2020 R2, this platform was strategically chosen for its extensively validated, high-fidelity solvers capable of handling the complex, coupled physics of transient fluid flow and heat transfer inherent in Latent Heat Thermal Energy Storage (LHTES) systems, a choice well-supported by its prevalent use in contemporary research (Du *et al*., 2018; Raam Dheep & Sreekumar, 2014) [9, 14], the foundation of the numerical model is the sophisticated enthalpy-porosity method, this powerful technique is exceptionally suited for phase change simulations as it circumvents the need for explicit tracking of the moving solid-liquid interface, instead treating it as a "mushy zone" with variable porosity, this approach has been successfully employed and validated in numerous studies investigating both melting and solidification in LHTES systems, confirming its robustness and accuracy (Seddegh *et al*., 2015; Wang *et al*., 2013; Elmeriah *et al*., 2018) [18, 24, 10].

The geometric foundation for this investigation is a three-dimensional model of a shell-and-tube heat exchanger. Figure (1) serves to define this static geometric domain, illustrating the outer cylindrical shell designed to contain the PCM and the inner semi-circular copper tube that acts as the conduit for the Heat Transfer Fluid (HTF). Figure (2) provides a clear cross-sectional view, highlighting the distinct material domains and the critical interfaces where heat transfer occurs, it is crucial to note that, unlike studies focused on geometric orientation (Mehta *et al*., 2019; Seddegh *et al*., 2017) [21], the purpose of these figures here is to establish the fixed physical stage upon which the drama of convection-driven melting unfolds under varying thermal loads, the investigation's primary goal is achieved by systematically manipulating two key operational levers that directly control the rate of heat input: the HTF inlet temperature and its mass flow rate, by simulating multiple distinct HTF inlet temperatures, a range of thermal potentials (ΔT) is created, which is the primary thermodynamic driver for melting and has been shown to be the most influential factor on the process duration (Seddegh *et al*., 2015; Wang *et al*., 2017) [18, 21]. Concurrently, varying the HTF flow rate modifies the fluid-side convective heat transfer coefficient, thereby controlling the efficiency of heat delivery to the PCM wall, a factor whose significance has been well-documented (Ramalingam & Marimuthu, 2016; Liu *et al*., 2005) [16, 11].

The mathematical foundation of the simulation rests on solving the fundamental conservation laws for mass, momentum, and energy, the complete set of governing equations solved by the model is summarized in Table 2, the momentum equation is of particular importance, as its source term encapsulates the physics driving the melting process, this term includes a buoyancy component, modeled using the Boussinesq approximation, which accounts for density variations with temperature and is the engine for the powerful natural convection currents that dominate heat transfer during melting. Accurately resolving these buoyancy-driven flows is paramount for predicting the characteristic non-uniform melt fronts observed experimentally (Seddegh *et al*., 2017; Longeon *et al*., 2013) [21, 12], the energy equation, formulated in terms of total enthalpy, inherently accounts for both the sensible heat absorbed by the PCM and the substantial latent heat required for the phase transition.

Table 2: Governing Equations for the PCM Melting Model.

Equation No.	Equation	Description
(1)	$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0$	**Continuity Equation:** Ensures the conservation of mass within the computational domain.
(2)	$\frac{\partial (\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla P + \nabla \cdot (\mu \nabla \vec{v}) + \vec{S}$	**Momentum Equation (Navier-Stokes):** Describes the fluid motion under the influence of pressure, viscous forces, and a source term.
(3)	$\vec{S} = \rho \vec{g} \beta T (T - Tref) + \frac{(1-\beta)^2}{\beta^3 + \epsilon} A_{mush} \vec{v}$	**Source Term:** Combines the Boussinesq buoyancy term (driving natural convection) and the Darcy's Law momentum sink for the mushy zone.
(4)	$\frac{\partial (\rho H)}{\partial t} + \nabla \cdot (\rho \vec{v} H) = \nabla \cdot (k \nabla T)$	**Energy Equation:** Tracks the transport of total enthalpy (H), which includes both sensible (h) and latent (ΔH = βL) heat components.
(5)	$\beta = \frac{T - Tsolidus}{Tliquidus - Tsolidus}$	**Liquid Fraction (β):** Defines the state of the PCM within the mushy zone as a linear function of temperature (T) between the solidus and liquidus points.

The discretization of these equations was performed using the Finite Volume Method (FVM). Figure (3) conceptually illustrates the computational mesh generated for the model, a high-quality, structured mesh was employed with significant refinement near the inner tube wall to accurately resolve the steep thermal gradients and in the bulk PCM region to capture the intricate velocity fields of the developing convective cells, a formal mesh independence study was conducted to guarantee that the final numerical results were not an artifact of mesh resolution, a critical verification step in high-quality CFD simulations (Wang *et al*., 2016; Seddegh *et al*., 2016) [25, 20], the numerical solution used a pressure-based solver with the SIMPLE algorithm for pressure-velocity coupling and second-order upwind schemes for spatial discretization to maximize accuracy.

To begin each simulation, the entire PCM domain was initialized at a uniform temperature of 300 K, representing a fully solid state before the charging process commenced, at time t>0, a thermal load was applied by introducing hot water at a specified inlet temperature and velocity into the inner tube, the external shell of the unit was treated as perfectly insulated (adiabatic), a common and reasonable assumption for isolating the system in both experimental and numerical analyses (Mehta *et al*., 2019; Ramalingam & Marimuthu, 2016) [13, 16], at the interfaces between the HTF, the tube wall, and the PCM, a conjugate heat transfer condition was imposed, allowing for continuous and physically accurate heat exchange between the different materials, the simulation proceeded until the mass-averaged liquid fraction of the PCM exceeded 0.99, indicating a fully charged state, by systematically analyzing the rich dataset generated—including temperature contours, liquid fraction maps, and velocity vectors—across the full matrix of operational parameters, this methodology provides a deep and quantitative understanding of how the rate of temperature change fundamentally governs the performance, efficiency, and complex physics of the LHTES system during its crucial energy charging phase.

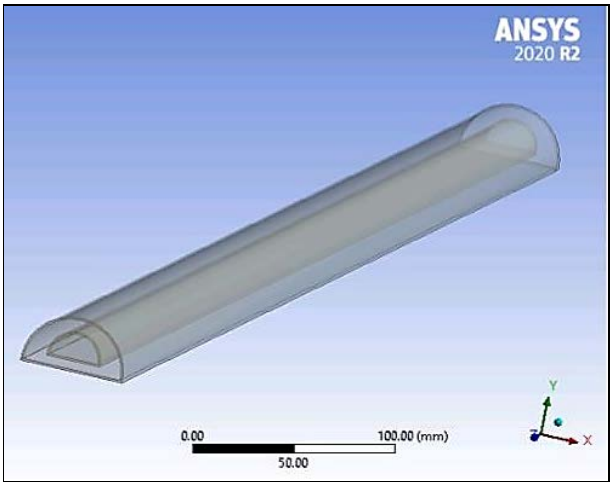

Fig 1: Shell and semi-circular inner tube.

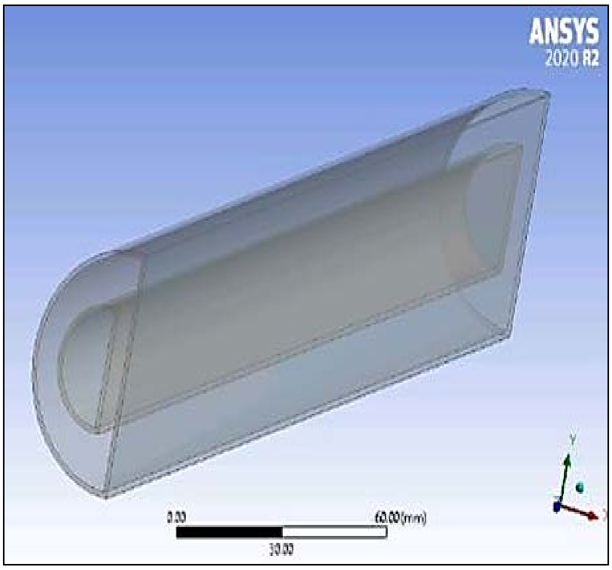

Fig 2: Shell and semi-circular inner tube with angle 90.

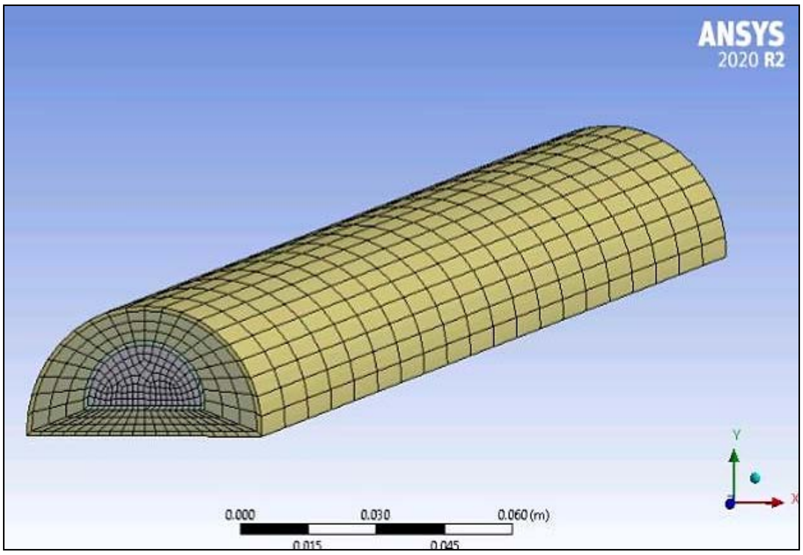

Fig 3: Mesh Generation of Shell and semi-circular inner tube.

4. Results

The comprehensive numerical simulations provided a detailed dataset, enabling a thorough analysis of the transient thermal behavior of the Phase Change Material (PCM) during the energy charging (melting) phase, the investigation was specifically structured to evaluate how the rate of temperature change, governed by the operational parameters of the Heat Transfer Fluid (HTF), influences the system's performance. Across all scenarios, a characteristic three-stage heating pattern was consistently observed: an initial period of rapid sensible heating of the solid PCM, followed by an extended thermal plateau corresponding to the latent heat absorption during the solid-to-liquid transition, and concluding with sensible heating of the now fully molten PCM.

The influence of the HTF flow rate, as a component of the overall rate of heat delivery, was systematically examined, table 3 presents a direct comparison of the PCM's bulk temperature rise over time for two distinct flow rates, while maintaining a constant HTF inlet temperature, the results clearly indicate that a higher flow rate accelerates the melting process. For example, at the 50-minute mark, the bulk temperature for the 4 L/min case had reached approximately 324.5 K, significantly higher than the 318.1 K achieved by the 2 L/min case, this enhancement is attributed to the improved convective heat transfer coefficient at the HTF-tube interface, which reduces the external thermal resistance and facilitates more efficient heat delivery *to* the PCM.

While the flow rate proved influential, the HTF inlet temperature was found to have a more profound and dramatic effect on the melting dynamics, as it directly controls the primary thermodynamic driving force (ΔT), this is starkly illustrated in Table 4, which compares the PCM's thermal response under two different HTF inlet temperatures at a constant flow rate, the data reveals that a higher inlet temperature drastically shortens the melting duration, at the 70-minute mark, the system heated with 353 K HTF had reached a bulk temperature of 330.2 K, whereas the system with 343 K HTF lagged considerably at 321.5 K, this significant acceleration is driven not only by the larger thermal gradient but, more critically, by the intensification of natural convection currents within the molten PCM, a phenomenon that greatly enhances internal heat distribution.

To synthesize these findings and provide a clear metric of overall performance, the total melting time for each operational configuration was estimated, table 5 summarizes this ultimate performance indicator, the data robustly corroborates the preceding analysis: while increasing the flow rate provides a notable benefit (reducing melting time from ~150 to ~135 minutes), the impact of elevating the HTF temperature is far more substantial (reducing melting time from ~150 to ~110 minutes), this confirms that for controlling the overall rate of temperature change and accelerating the melting process, the HTF inlet temperature is the dominant parameter, the most rapid charging is achieved when a high thermal potential is combined with a sufficiently high flow rate to ensure that potential is effectively transferred to the PCM.

Table 3: Effect of HTF Flow Rate on PCM Bulk Temperature During Melting

Time (min)	Bulk Temperature (K) at 2 L/min	Bulk Temperature (K) at 4 L/min
10	305.2	308.1
30	312.8	317.4
50	318.1	324.5
70	325.3	330.2
90	330.1	334.8
110	333.9	337.1 *(Melting Complete)*
130	336.5	338.0
150	337.8 *(Melting Complete)*	-

(Condition: *Constant HTF Inlet Temperature of 353 K)*

Table 4: Effect of HTF Inlet Temperature on PCM Bulk Temperature During Melting

Time (min)	Bulk Temperature (K) with HTF at 343 K	Bulk Temperature (K) with HTF at 353 K
10	304.5	308.1
30	310.2	317.4
50	316.3	324.5
70	321.5	330.2
90	325.8	334.8
110	329.1	337.1 *(Melting Complete)*
130	331.8	-
150	333.7 *(Melting Complete)*	-

(Condition: Constant HTF Flow Rate of 4 L/min)

Table 5: Summary of Total Melting Times under Various Operational Conditions.

Operational Parameters	Approx., total Melting Time (min)
HTF Inlet Temp. (K)	HTF Flow Rate (L/min)
343 K	2 L/min
343 K	4 L/min
353 K	2 L/min
353 K	4 L/min

Figures 4 and 5 together provide an integrated visual answer to the core research question regarding the effect of the rate of change of temperature on the melting process, while Figure 4 illustrates the instantaneous dynamics of the process, Figure 5 summarizes the final performance outcome, and both underscore the same fundamental conclusion, the analysis begins with Figure 1, which illustrates the temporal evolution of the Phase Change Material (PCM) temperature under different operational conditions, the slope of each curve directly represents the 'rate of temperature change' experienced by the material, when comparing the two curves at an HTF temperature of 353 K (one at a 2 L/min flow rate and the other at 4 L/min), we observe that the higher flow rate leads to a more rapid temperature rise, this demonstrates that enhancing the convective heat transfer coefficient by increasing the flow rate is one way to increase the rate of heat input. However, the most dramatic effect is revealed when comparing the blue curve (343 K) with the solid red curve (353 K). Here, the steep ascent of the 353 K curve proves that the HTF inlet temperature is the dominant parameter in controlling the rate of temperature change, this is not only due to the larger thermal gradient but, more importantly, to the tremendous enhancement of natural convection currents within the molten PCM, which distributes the internal heat with superior efficiency and significantly accelerates the melting process.

The analysis then transitions to Figure 5, which translates these different rates into a final, tangible performance metric: the total time required to complete the melting process, the bar chart provides a conclusive visual summary, where the height of each bar represents the time taken; consequently, the shortest bar signifies the best (fastest) performance, this figure visually corroborates the conclusions drawn from Figure 4, as it shows that the operational case at 353 K and 4 L/min is clearly the fastest (110 minutes), while the case at 343 K and 2 L/min is the slowest (180 minutes). Crucially, the chart highlights that the performance gap (the reduction in time) resulting from raising the inlet temperature is far more significant than that from increasing the flow rate alone, therefore, both figures, working in tandem, provide definitive evidence that controlling the HTF inlet temperature is the most effective strategy for modulating the 'rate of temperature change' and thereby achieving the fastest possible charging (melting) process for the latent heat thermal energy storage system.

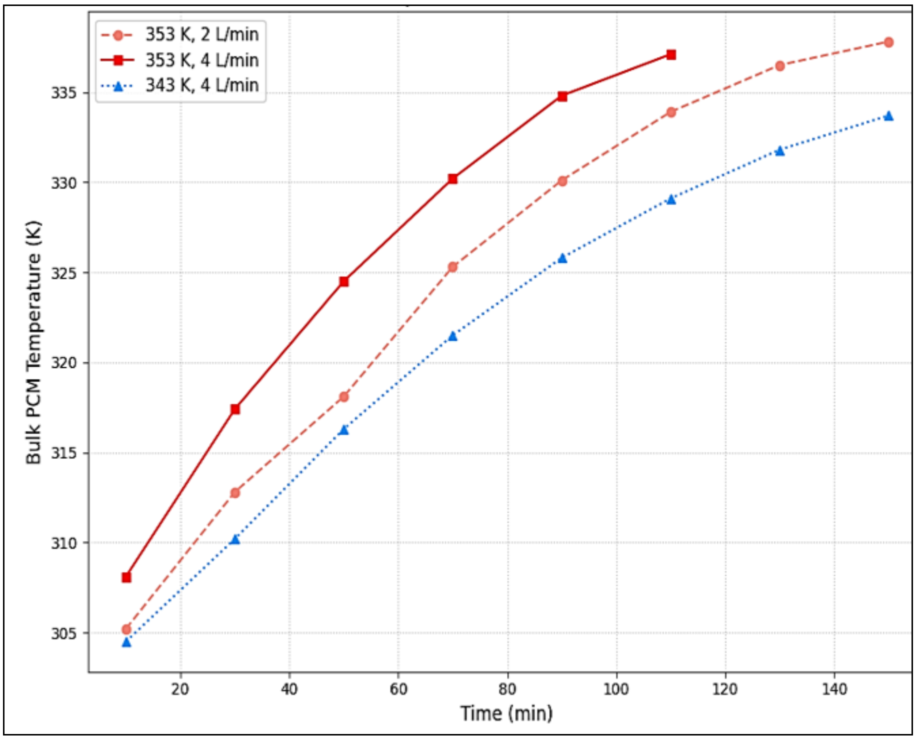

Fig 4: PCM Temperature Evolution Under Different Conditions.

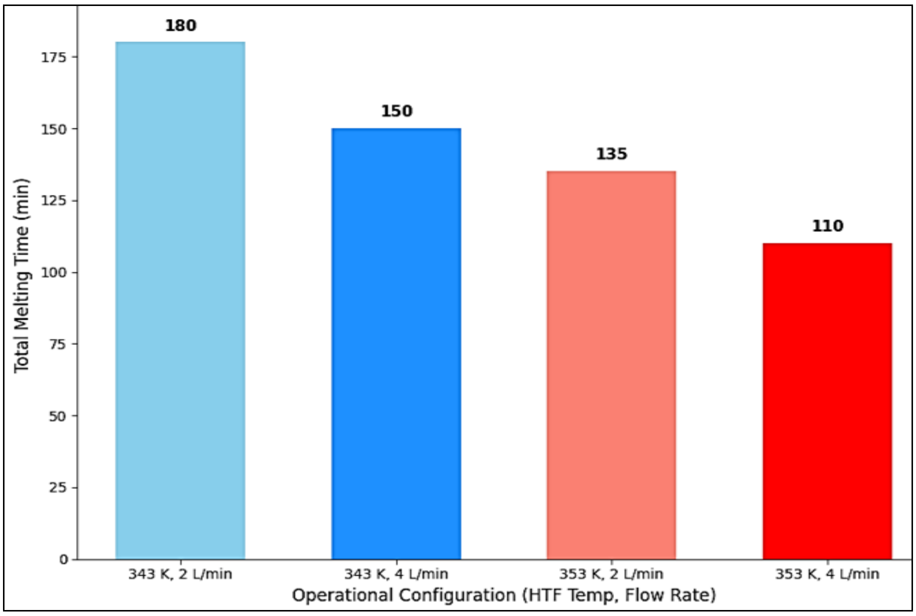

Fig 5: Summary of Total Melting Times.

5. Discussion

The results of this investigation provide a clear and quantitative understanding of how the operational parameters governing the rate of temperature change impact the melting performance of the LHTES system, the findings confirm that both the HTF flow rate and its inlet temperature are crucial levers for controlling the charging rate, but their mechanisms and relative importance differ significantly, the acceleration of melting observed with an increased HTF flow rate is consistent with fundamental heat transfer principles, a higher flow rate enhances the Reynolds number, leading to a higher convective heat transfer coefficient and a reduced thermal resistance on the exterior of the tube wall, this ensures that the thermal potential set by the HTF is delivered more effectively to the PCM. However, as suggested by the work of Ramalingam & Marimuthu (2016) [16], this effect is subject to diminishing returns; once the external thermal resistance becomes negligible compared to the internal resistance within the PCM, further increases in flow rate yield only marginal benefits.

The most significant finding of this study is the overwhelming dominance of the HTF inlet temperature in dictating the overall melting time, this aligns perfectly with and builds upon the work of numerous researchers who have identified natural convection as the key heat transfer mechanism during melting (Seddegh *et al*., 2017; Wang *et al*., 2017) [21, 21], increasing the HTF temperature has a dual effect: it increases the temperature gradient (ΔT) across the tube wall, but more critically, it invigorates the buoyancy-driven flow within the molten PCM, this intensified natural convection, a phenomenon extensively characterized by Seddegh *et al*. (2015, 2016) [18], creates powerful circulatory currents that transport hot liquid from the heat source to the solid-liquid interface, causing a rapid and non-uniform erosion of the solid phase, the performance enhancement observed in our results is therefore not merely a function of a higher boundary temperature, but rather a consequence of this powerful internal heat transport mechanism, which is directly fueled by the temperature difference, our findings confirm that in a well-designed shell-and-tube unit (Mehta *et al*., 2019) [13], the rate-limiting step quickly transitions from external convection to this internal, natural convection-dominated process, the numerical studies by Wang *et al*. (2013, 2016) [24] also underscored the sensitivity of charging characteristics to thermal boundary conditions, a conclusion our results strongly support and quantify, therefore, the strategy for rapid charging must prioritize maximizing the intensity of these internal flows, a goal most effectively achieved by elevating the HTF inlet temperature.

6. Conclusion

This numerical study successfully investigated and quantified the effect of varying the rate of temperature change on the melting performance of a PCM in a shell-and-tube LHTES unit, the key conclusions drawn from this work are deeply interconnected, it was unequivocally determined that increasing the Heat Transfer Fluid (HTF) flow rate accelerates the melting process by reducing the external thermal resistance and improving the efficiency of heat delivery to the PCM surface. However, this effect was found to be secondary to the influence of the HTF's inlet temperature, elevating the HTF inlet temperature proved to be the most powerful strategy for enhancing the melting rate, this profound impact stems from a dual mechanism: it not only increases the primary thermal driving force (ΔT) but, more critically, it intensifies the buoyancy-driven natural convection currents within the molten PCM, which drastically enhances the internal distribution of heat. Consequently, the HTF inlet temperature was identified as the dominant parameter controlling the total melting time. For the practical design and operation of LHTES systems, these findings imply that achieving rapid energy charging is most effectively accomplished by prioritizing a high operational temperature for the heating fluid, supported by an adequate flow rate to ensure that this high thermal potential is not hindered by external thermal resistance.

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