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A Parametric Study on The Performance of Latent Heat Thermal Energy Storage

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ABSTRACT

Thermal energy storage (TES) systems play a crucial role in sustainable energy management by storing excess energy for later use, improving overall efficiency, reducing emissions, and enhancing grid reliability. Among TES technologies, latent heat thermal energy storage (LHTES) systems are particularly attractive due to their high energy storage capacity and ability to operate at nearly constant temperatures. However, the low thermal conductivity of phase change materials (PCMs) remains a significant challenge, limiting the rate of heat transfer and overall system performance. This study explores the performance of an LHTES system by examining the effects of inlet temperature, mass flow rate, and flow direction, with a particular focus on horizontal flow configurations. The aim is to identify optimal parameter settings that enhance heat transfer efficiency and improve system performance. Using ANSYS Fluent, numerical simulations were conducted with paraffin wax RT82 as the PCM and copper as the triplex tube heat exchanger material. The results showed that an optimized parameter combination reduced the melting time to 232.8 minutes, a 51.44% improvement over the baseline case. These findings highlight the potential for strategic parameter optimization to significantly enhance LHTES efficiency by accelerating PCM melting and improving thermal distribution. This study provides valuable insights into optimizing LHTES system performance, contributing to the development of more effective energy storage solutions that minimize energy losses and improve thermal management.

Keywords: Latent Heat Thermal Energy Storage, Phase Change Material, Triplex Tube Heat Exchanger.

1. INTRODUCTION

Ensuring a stable and sustainable energy supply is becoming an increasingly urgent challenge, as current energy production and consumption patterns place significant economic, environmental, and social pressures on modern societies. With rising global energy demand driven by population growth and industrial expansion, there is a strong need for efficient energy storage solutions that can help reduce carbon emissions and enhance grid stability. Among the various energy storage technologies, Thermal Energy Storage (TES) systems stand out for their ability to store surplus energy during off-peak hours and release it during peak demand periods, thereby reducing reliance on fossil fuels and lowering greenhouse gas emissions. TES has already found widespread application in solar energy storage, district heating and cooling, and industrial waste heat recovery, making it a key component of future energy management strategies.

TES technologies are generally classified into three main categories: sensible heat storage, latent

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heat storage (LHS), and thermo-chemical storage, each with distinct advantages depending on the application. Latent Heat Thermal Energy Storage (LHTES), in particular, has gained considerable attention due to its high energy storage density and ability to operate at nearly constant temperatures, making it well-suited for solar thermal power plants, building energy systems, and industrial heat management [1]. Phase Change Materials (PCMs), which absorb and release heat during phase transitions, play a central role in LHTES systems, allowing for efficient heat storage and retrieval [2].

Despite these advantages, one of the biggest limitations of PCMs is their low thermal conductivity, which significantly slows down heat transfer, leading to longer charging and discharging times [3]. Various approaches have been explored to improve heat transfer efficiency in LHTES systems, such as embedding high-conductivity materials (e.g., metal foams, nano-additives), incorporating extended surface structures (e.g., fins, porous media), and optimizing heat exchanger designs [4-5]. While these methods have shown promise, further refinements are still needed to enhance overall system performance, particularly in terms of energy transfer rates and response times. Recent research has highlighted the importance of flow direction, inlet temperature, and mass flow rate in improving heat transfer in LHTES systems, but a comprehensive evaluation of these parameters remains limited.

This study aims to investigate the effects of flow direction, inlet temperature, and mass flow rate on LHTES system performance using numerical simulations with ANSYS Fluent. Paraffin wax RT82 is selected as the PCM, with copper serving as the triplex tube heat exchanger material, to evaluate how these parameters influence heat transfer efficiency and phase change behavior. The primary objective is to identify optimal parameter configurations that accelerate the melting processes, reduce thermal response times, and improve overall system efficiency. The insights gained from this study will contribute to the advancement of high-performance LHTES systems, supporting the development of more efficient and scalable thermal energy storage solutions for renewable energy applications and industrial waste heat recovery.

2. METHODOLOGY

This study employs a simulation-based approach to optimize the key operational parameters influencing the performance of Latent Heat Thermal Energy Storage (LHTES) systems using a triplex tube heat exchanger (TTHX) and paraffin wax RT82 as the phase change material (PCM). The research is structured into two main phases: (1) the modeling phase and (2) the simulation and analysis phase.

Phase 1: Geometry Development and Meshing

In the first phase, the geometry of the TTHX is designed using ANSYS Workbench's DesignModeler tool. The heat exchanger consists of three concentric tubes: an outer tube, an intermediate tube containing the PCM, and an inner tube. The heat transfer fluid (HTF) circulates through the inner and outer tubes, while the intermediate tube serves as the PCM reservoir, facilitating heat exchange through phase transition processes.

Once the geometric model is established, meshing is performed using ANSYS Mesh, ensuring an appropriate balance between computational accuracy and efficiency. The mesh quality is carefully refined to minimize numerical diffusion and achieve converged, high-resolution results in subsequent simulations.

Phase 2: Simulation and Performance Analysis

The second phase involves conducting computational fluid dynamics (CFD) simulations using

ANSYS Fluent to evaluate heat transfer characteristics and system performance. Initially, a baseline simulation is carried out to validate the numerical model against experimental data [1] and previous numerical studies [6]. The validation process ensures the accuracy and reliability of the computational setup before proceeding with further parametric studies.

Following validation, the study systematically investigates the impact of three critical parameters on LHTES performance:

a. Inlet Temperature: Examines how variations in HTF temperature influence PCM melting and energy storage efficiency.
b. Flow Direction: Compares the effects of parallel and counterflow configurations to determine the optimal flow arrangement for enhanced heat transfer.
c. Mass Flow Rate: Analyses the influence of different HTF flow rates on thermal response time and phase transition dynamics.

The results from these simulations provide valuable insights into optimizing LHTES system configurations, aiming to enhance heat transfer efficiency, shorten phase change durations, and improve overall thermal management performance. The findings contribute to the advancement of thermal energy storage technologies, particularly for renewable energy applications and industrial waste heat recovery.

2.1 Geometry Modelling

The geometry of the triplex tube heat exchanger (TTHX) was designed using DesignModeler in ANSYS software, as illustrated in (Figure 1). The TTHX features an inner pipe with a diameter of 50.8 mm, an intermediate pipe with a diameter of 150 mm, and an outer pipe with a diameter of 200 mm. The thickness of the intermediate and outer pipes is 2 mm each, while the inner pipe has a thickness of 1.2 mm. The detailed dimensions of the TTHX are presented in Table 1, based on specifications from a previous experimental study [7]. The intermediate pipe is filled with phase change material (PCM), while the outer and inner pipe are filled with heat transfer fluid (HTF).

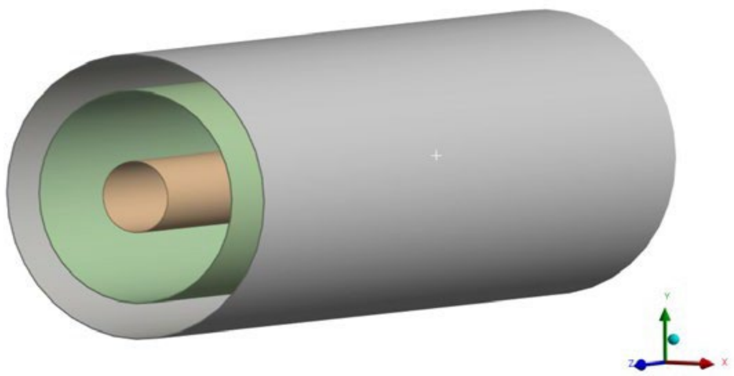


Figure 1: An isometric view of the triplex tube heat exchanger.

Table 1: The dimensions of the triplex tube heat exchanger

Tube	Diameter	Thickness	Length
Outer Pipe	200 mm	2 mm	500 mm
Middle Pipe	150 mm	2 mm	500 mm
Inner Pipe	50.8 mm	1.2 mm	500 mm

2.2 Computational Model and Numerical Solution Method

Simulations were conducted in Ansys Fluent using pressure-based and transient options to capture the time-dependent behavior of phase change and heat transfer. Gravity was set at -9.81 m/s^2 along the Y-axis, and the energy equation was enabled. The laminar melting process (Re = 3410.96) was modelled with solidification and melting enabled. The cell zone conditions were divided into liquid and solid. The model setup detail is explained in Table 2. Water-liquid, as the heat transfer fluid, flowed through the outer and inner tubes, while paraffin wax RT82 in the intermediate tube acted as the phase change material to store and release thermal energy. Water-liquid properties used Fluent's default settings, while properties for paraffin wax RT82 and copper (used for all three tubes) were specified, as shown in Tables 3 and Table 4, respectively.

Table 2: Model setup.

Solver	Pressure Based Solver
Time	Transient Analysis
Gravity	-9.81 m/s^2 (y-direction)
Solver	Laminar Flow
	Solidification & Melting
	Energy

Table 3: Properties of paraffin RT82.

Property Material	Material: RT82
Latent heat of fusion, L[kJ/kg]	176
Dynamic viscosity, μ[N.s/m^2]	0.03499
Density, ρ[kg/m^3]	770
Thermal conductivity, k [W/m K]	0.2
Thermal expansion coefficient, β[1/K]	0.001
Solid temperature, T_s[K]	350
Liquid temperature, T_l[K]	358
Specific heat capacity of liquid, C_{pl}[J/kg K]	2

Table 4: Material properties of copper.

Property Material	Material: RT82
Density, ρ[kg/m^3]	8978
Thermal conductivity, [W/m K]	387.6
Specific heat capacity of liquid, C_{pl}[J/kg K]	381

2.2.1 Simulation Model

To simplify the mathematical formulation of the model, the following assumptions are adopted: (1) the PCM melt flow is treated as laminar, unsteady, and incompressible; (2) temperature variations within the heat transfer fluid (HTF) are considered negligible; (3) the thermophysical properties of the PCM are assumed constant across the investigated temperature range, with density variations of the liquid PCM approximated using the Boussinesq assumption; and (4) viscous dissipation, volumetric expansion upon phase change, radiative heat exchange, and heat losses through the external shell wall are neglected.

2.2.2 Initial Condition and Boundary Condition

The detailed initial and boundary conditions employed for the charging (melting) process are summarized in Table 4. At the initial state (t = 0), the phase change material (PCM) is uniformly maintained at an ambient temperature of 300 K, corresponding to a subcooled state situated 50 K) below its solidus temperature (T_s). This ensures the PCM is initially in a fully solidified condition (6).

Thus, the initial temperature condition is explicitly defined as:

At $t = 0$, $T = T_{initial} = 300$ K

For subsequent time intervals (t >0), both the inner and outer surfaces of the annular enclosure are exposed to a uniform wall temperature of Tw=366 K, which remains constant throughout the melting process. The selection of this boundary temperature is based on the minimal operational temperature requirement (T≥65∘C) necessary to effectively drive solar-powered liquid-desiccant air conditioning systems [7][8][9].

Consequently, the boundary conditions during charging are formulated as:

(1) at $r = r_i, T = T_W = 343$ K

(2) at $r = r_o, T = T_W = 343$ K

Given that the imposed boundary temperature (T_w) exceeds the liquidus temperature (T_ℓ), melting commences simultaneously at both the inner and outer walls of the annulus. This leads to progressive melting fronts advancing inward from the surfaces into the solid PCM region, resulting in the development and subsequent expansion of a mushy (partially melted) zone. Heat transfer during this melting phase involves conduction within the solid PCM, while in the liquid region, both conduction and buoyancy-driven natural convection contribute significantly to the overall energy transport due to temperature-induced density gradients.

Table 4: Initial and Boundary Condition.

Boundary Condition	**Charging Process**
Inlet HTF Temperature	366 K
Initial PCM Temperature	300 K
Outer Pipe Temperature	366 K (Adiabatic Process)
Container Material	Copper

2.2.3 Solution Method

In this study, the numerical simulations were performed using the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) scheme, chosen for its efficiency and reliability in modeling incompressible flow regimes. For the discretization of the pressure correction equation, the Pressure Staggering Option (PRESTO) scheme was adopted due to its demonstrated capability to accurately predict pressure fields, particularly in buoyancy-driven convective systems. Additionally, to discretize the momentum and energy equations within Ansys Fluent, the

Quadratic Upstream Interpolation for Convective Kinematics (QUICK) scheme—a second-order upwind method was applied. The QUICK scheme was specifically selected to improve solution accuracy by effectively minimizing numerical diffusion, which is critical in convective heat transfer simulations.

For initialization, Fluent's standard initialization method was applied, assigning a uniform initial temperature of 366 K across all computational cells. Based on preliminary trials and sensitivity checks, a fixed time step size of 0.3 s was found appropriate. This value ensured numerical stability, promoted consistent convergence, and provided a reliable balance between computational efficiency and accuracy throughout the entire simulation period.

2.3 Benchmarking and Grid Sensitivity Analysis

A grid sensitivity analysis was conducted to assess the influence of mesh resolution on the numerical accuracy and computational efficiency of the simulation model. The results of this analysis are illustrated in Figure 2, where four different mesh configurations were examined: coarse (457,045 elements), medium (773,760 elements), fine (1,364,000 elements), and very fine (1,764,281 elements).

The convergence study, based on the liquid fraction result (Figure 2), revealed that the fine mesh resolution was sufficient to accurately capture the phase change behavior under the given simulation conditions. While the very fine mesh offered marginal improvements, the associated increase in computational cost was not justified. The simulation results showed that the very fine mesh required 152 minutes for complete melting, which was only 1 minute faster than the fine mesh. In contrast, the medium and coarse meshes exhibited longer melting times of 163 minutes and 165 minutes, respectively. The minimal discrepancy between the fine and very fine meshes indicates that further refinement does not yield significant benefits in terms of accuracy but imposes a higher computational burden.

Based on this analysis, the fine mesh configuration (1,364,000 elements) was selected as the optimal discretization strategy, balancing computational efficiency and solution accuracy. This meshing scheme was adopted as the baseline for the charging process, ensuring reliable results while minimizing computational costs.

A rigorous benchmarking process was conducted to validate the accuracy of the developed numerical model in predicting the thermo-fluidic behavior of phase change material (PCM) within a triplex tube heat exchanger. The validation procedure was aligned with the experimental study conducted by Al-Abidi et al. (2013) [7], which, to the best of the authors' knowledge, represents the only documented experimental investigation into the charging of a triplex tube via both its inner and outer pipes.

The present simulation model was validated by adopting the same initial conditions, boundary conditions, and thermo-physical properties utilized in Al-Abidi et al.'s (2013) study (Figure 3). This approach ensures a direct comparison between numerical predictions and experimental observations, thereby reinforcing the credibility of the model. Given the limited availability of experimental data in this domain, Al-Abidi et al.'s (2013) findings serve as a fundamental reference for evaluating the predictive accuracy of the present numerical framework. This validation strategy enhances the model's reliability and establishes a robust foundation for future investigations into PCM-based thermal energy storage applications.

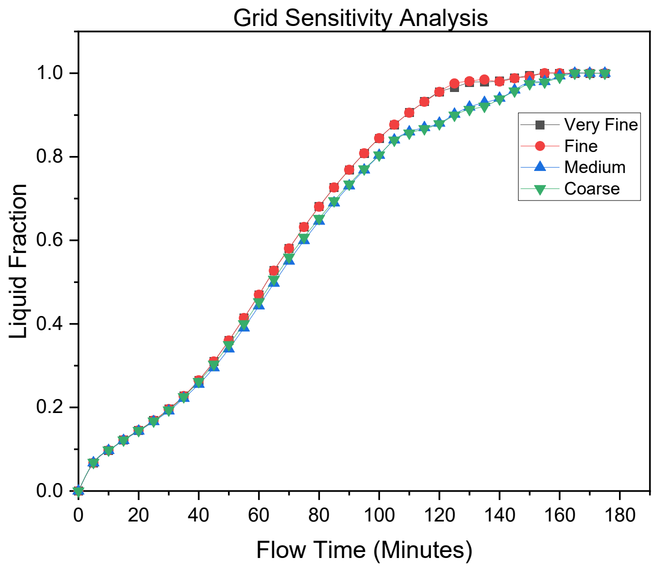


Figure 2: Grid Sensitivity Analysis for the Melting Process.

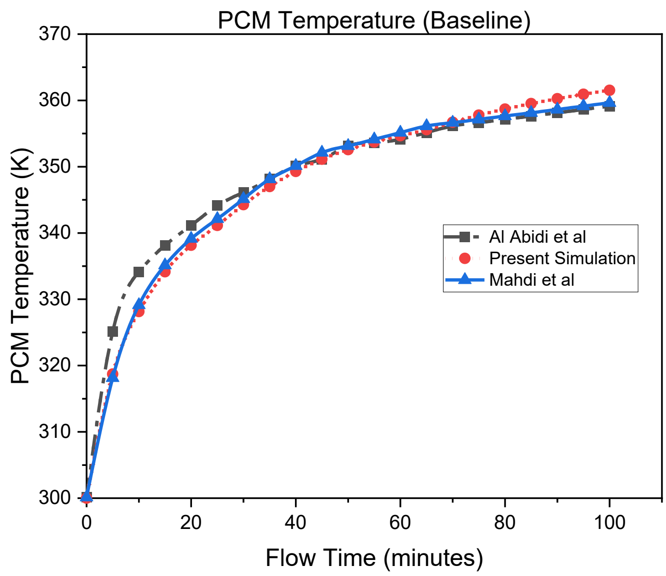


Figure 3: Baseline comparison between the current simulation and the experimental data from Al abidi et al. (2013).

2.4 Simulation Parameter Study

2.4.1 Flow Direction

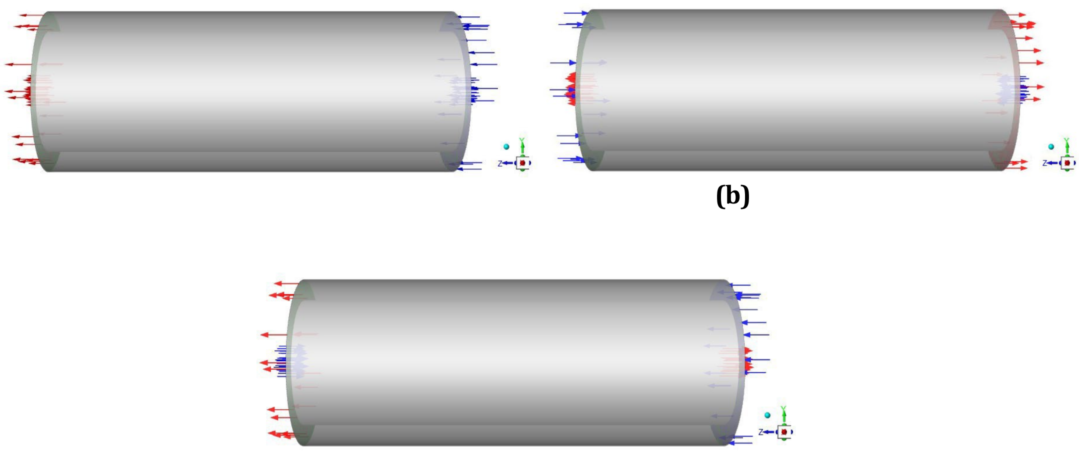
The influence of flow direction on the performance of latent heat thermal energy storage was investigated by analyzing three distinct flow configurations: "two opposite," "inner opposite," and "outer opposite." In the "two opposite" arrangement, fluid within both the inner and outer tubes flows in opposing directions, as depicted in Figure 4(a). For the "inner opposite" configuration, only the inner tube flow direction is reversed relative to the outer tube [see Figure 4(b)], whereas, in the "outer opposite" scenario, it is the outer tube flow that is reversed [refer to Figure 4(c)].

Boundary conditions for each configuration were adjusted accordingly. Specifically, in the "two opposite" case, both inner and outer tube inlets were designated as outflow boundaries, with their respective outlets set as mass flow inlets. Conversely, in the "inner opposite" configuration, solely the inner tube inlet was defined as outflow, while the "outer opposite" configuration involved setting only the outer tube inlet as outflow. By systematically varying these flow conditions, the study aimed to identify the optimal arrangement that enhances thermal performance during the storage and retrieval of latent heat energy.

2.4.2 Inlet temperature

To thoroughly examine the influence of inlet temperature on the thermal performance of latent heat thermal energy storage, a parametric study was conducted by varying the inlet temperature. Simulations were performed for selected inlet temperatures of 358 K, 368 K, and 373 K, compared against a baseline scenario of 363 K. These specific temperature variations were carefully chosen to provide insight into how the inlet temperature affects PCM melting behaviors, the dynamics of phase transition, and overall heat-transfer efficiency within the system.

Adjustments were implemented at the boundary conditions, particularly at the inlet regions of the inner and outer tubes. Standard initialization within Ansys Fluent was employed, whereby the initial temperature across the computational domain was uniformly set equal to the respective inlet temperature used in each scenario, computed consistently from all zones. Through this approach, the analysis offered an in-depth understanding of the PCM's response to different thermal boundary conditions, enabling the identification of the most effective inlet temperature for enhanced thermal energy storage performance.



(a) (b) (c)

Figure 4: (a) Two opposite flow direction, (b)Inner opposite flow direction, and (c) Outer opposite flow direction.

2.4.3 Mass Flow Rate

Table 5 presents the value of the mass flow rate involved in the simulation for a detailed parametric investigation into the influence of mass flow rate on latent heat thermal energy storage performance. The simulations specifically examine how variations in the mass flow rate impact the temperature distribution and the liquid fraction evolution of the PCM. For each scenario, adjustments to the mass flow rate boundary conditions were systematically applied at both the inner and outer tube inlets, with values expressed in units of kg/s.

The numerical study maintained consistency by employing identical solver settings, discretization schemes, and computational methods as established in the baseline scenario. This approach allowed for direct comparison and clear assessment of how incremental changes in the mass flow rate influence critical thermal parameters, such as the PCM's melting behavior, heat transfer effectiveness, and overall thermal storage performance.

Table 5: Different mass flow rates.

Case Study	Mass Flow Rate
Baseline	0.133 kg/s
1	0.083 kg/s
2	0.167 kg/s
3	0.25 kg/s
4	0.333 kg/s
5	0.417 kg/s
6	0.5 kg/s

3. RESULTS AND DISCUSSION

3.1 Parameter Study

3.1.1 Mass Flow Rate

This investigation evaluates the impact of varying mass flow rates on the thermal performance of latent heat thermal energy storage (LHTES), specifically emphasizing the optimization of melting duration and associated temperature profiles. Numerical simulations were systematically performed using ANSYS Fluent, considering mass flow rates ranging incrementally from 0.083 kg/s to 0.5 kg/s at intervals of 0.05 kg/s, while maintaining all other boundary conditions constant. The results demonstrate that increasing the mass flow rate notably enhances heat transfer rates, thereby shortening the total melting period (approximately 463.8 minutes for higher flow rates versus around 475.4 minutes at lower flow conditions).

Conversely, it was observed that lower mass flow rates tended to yield more uniform and stable temperature profiles within the PCM. Nevertheless, despite these temperature variations, the elevated mass flow rates contributed significantly to quicker melting due to improved convective heat transport into the PCM. Figure 5 presents the temporal evolution of the liquid fraction for each mass flow rate investigated. Initially, all curves exhibited closely aligned melting behavior until approximately the 450-minute mark, after which clear differences in average liquid fractions became discernible. By 500 minutes, all simulated cases reached complete melting (liquid fraction = 1), with melting durations consistently ranging from 463 to 480 minutes, as summarized quantitatively in Table 6. To further elucidate these observations, Figure 6 provides liquid fraction contours for three representative mass flow rates (0.083 kg/s, 0.25 kg/s, and 0.5 kg/s) at selected intervals (60, 180, 300, and 400 minutes). Although instantaneous differences were minimal, the selected broader intervals distinctly illustrate the progression of melting and highlight the influence of flow rate variation on PCM melting patterns over the complete process [10].

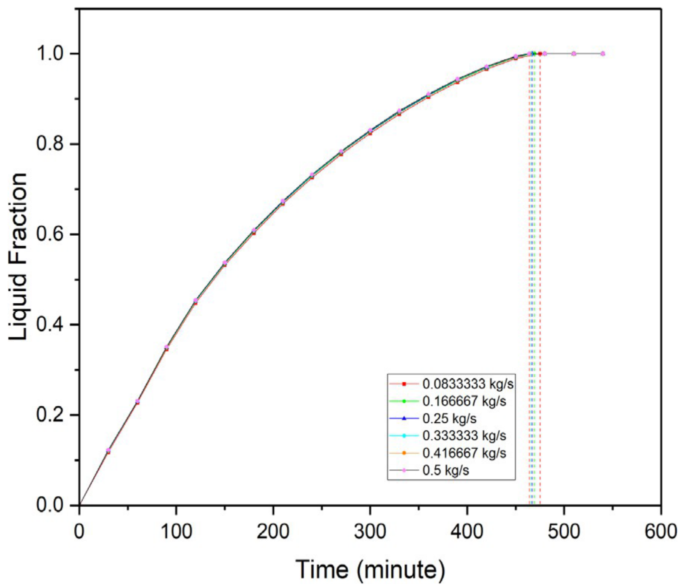


Figure 5: Liquid Fraction graph for different mass flow rates.

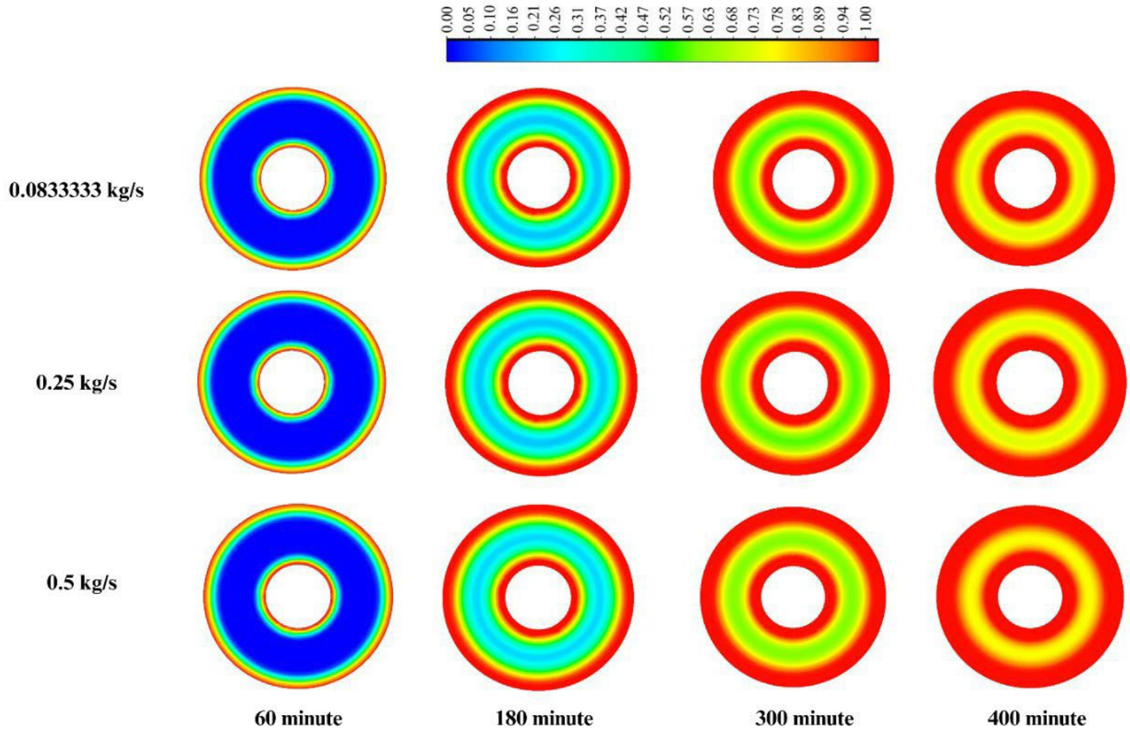


Figure 6: Contour liquid fraction of mass flow rate.

Table 6: Comparison results of different mass flow rates.

Mass Flow Rate	Temperature	Melting Completion Time	Improvement Percentage
Baseline	360.34 K	479.4 minute	-
0.083 kg/s	360.74 K	475.2 minute	0.88%
0.167 kg/s	360.65 K	469.5 minute	2.07%
0.250 kg/s	360.60 K	467.1 minute	2.57%
0.333 kg/s	360.59 K	465.9 minute	2.82%
0.417 kg/s	360.56 K	464.7 minute	3.07%
0.500 kg/s	360.53 K	463.8 minute	3.25%

3.1.2 Flow Direction

This study explored the influence of varying fluid flow directions on the melting performance of a phase change material (PCM) within a triplex tube heat exchanger. Numerical simulations were systematically performed to investigate three distinct flow configurations: “two opposite,” “inner opposite,” and “outer opposite,” as detailed in Table 7, with all other operational parameters maintained consistently. Figure 7(a) presents a comparative analysis of temperature evolution across these configurations, highlighting notable differences in melting durations attributed solely to changes in flow direction.

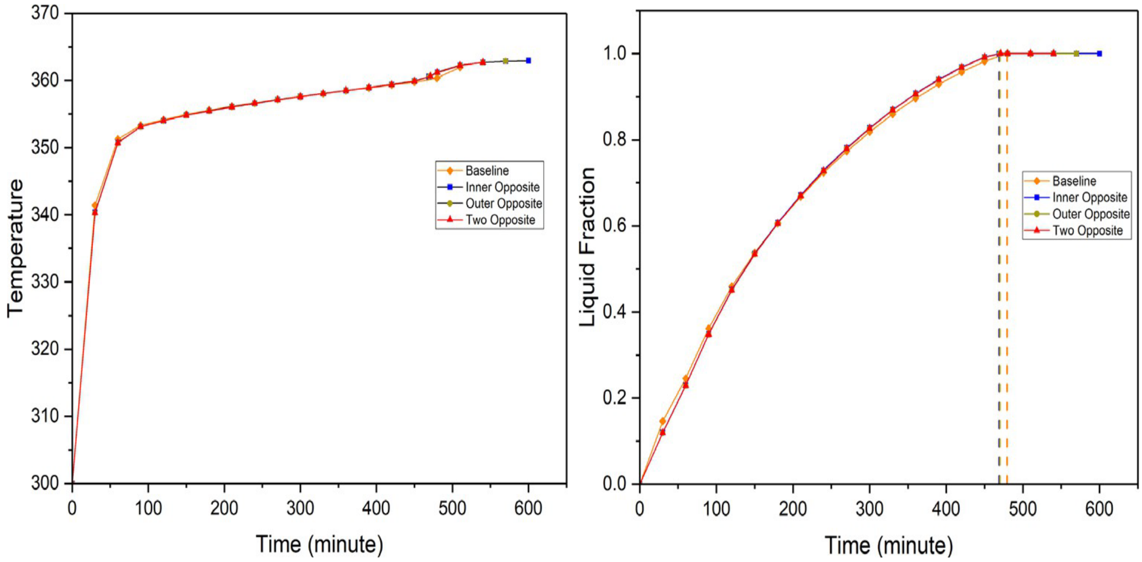
The results demonstrate that the “two opposite” configuration exhibited the longest PCM melting time, reaching full melting at approximately 471 minutes. In comparison, both the “outer opposite” and “inner opposite” configurations significantly improved melting rates, reducing the overall melting duration by roughly 2.00% and 2.19%, respectively. Among these, the “inner opposite” arrangement was identified as the optimal configuration, achieving the shortest melting completion time of 468.9 minutes, clearly indicating superior thermal performance and efficiency.

The findings underscore the critical role that fluid flow direction plays in optimizing the melting process within latent heat thermal energy storage (LHTES) systems. Although both the “two opposite” and “outer opposite” configurations provided improved performance compared to baseline conditions, their efficiencies remained somewhat lower than the “inner opposite” configuration. These insights confirm that strategic selection of flow orientation can significantly enhance melting performance, thus improving the reliability and overall effectiveness of LHTES applications.

Table 7: Result of flow direction analysis.

Flow Direction	Temperature	Melting Completion Time	Improvement Percentage
Baseline	360.34 K	479.4 minutes	-
Two Opposite	360.65 K	471 minutes	1.75%
Inner Opposite	360.56 K	468.9 minutes	2.19%
Outer Opposite	360.57 K	469.8 minutes	2.002%

Figure 7(b) illustrates a comparative analysis of liquid fraction evolution for the different flow-direction configurations, clearly indicating that the “inner opposite” setup achieves the fastest complete melting among the studied cases. Although all flow-direction scenarios follow a similar overall trend and closely match the baseline behavior, distinct variations emerge at specific intervals. The liquid fraction data, recorded at consistent 30-minute intervals, reveals that during the initial 150 minutes, the baseline scenario exhibits a higher liquid fraction than the alternative flow-direction cases. However, from approximately 250 minutes onward, the alternative flow configurations surpass the baseline performance, demonstrating enhanced melting rates due to optimized fluid flow orientation. These findings highlight the substantial impact that strategic adjustments in flow direction have on enhancing melting efficiency within latent heat thermal energy storage (LHTES) systems [11].



(a) (b)

Figure 7: (a) Comparison results of the temperature of different flow directions, and (b) Comparison liquid fraction of different flow directions.

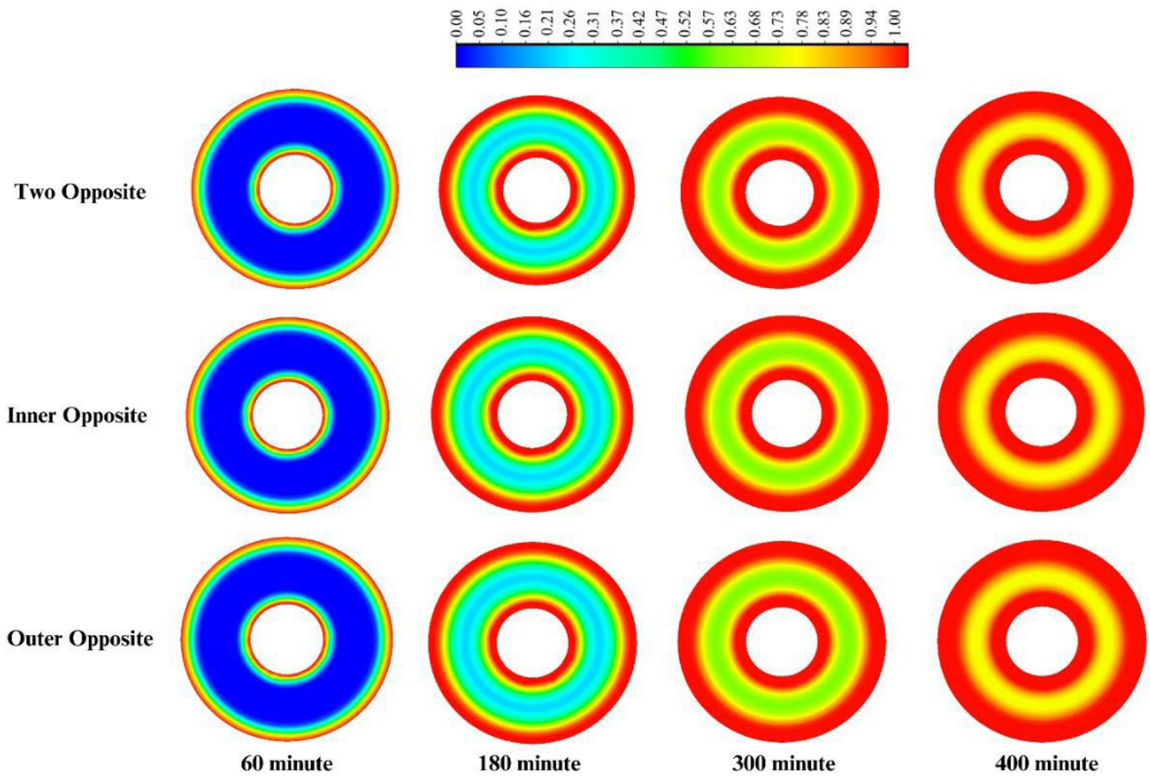


Figure 8: Contour Liquid Fraction of different flow directions.

Additionally, Figure 8 presents liquid fraction contour plots illustrating PCM melting progression for the three studied flow-direction configurations at selected time intervals: 60, 180, 300, and 400 minutes. These contours reveal a largely uniform melting pattern across all scenarios, with minimal noticeable differences between configurations at each interval. By the 400-minute mark, the PCM approaches nearly complete melting, as reflected by liquid fraction values ranging from approximately 0.78 to 1. Notably, the melting process predominantly initiates and advances from the inner and outer tube interfaces inward, ensuring effective heat penetration and thorough melting of the PCM. The contour plots thus provide critical insights into the interplay between flow-direction arrangements and thermal performance, emphasizing the importance of carefully optimizing flow direction to enhance the reliability and effectiveness of LHTES systems.

3.1.3 Inlet Temperature

The inlet temperature of the heat transfer fluid (HTF) plays a pivotal role in determining the performance and effectiveness of latent heat thermal energy storage (LHTES) systems. Specifically, higher HTF inlet temperatures increase the temperature gradient between the fluid and the phase change material (PCM), promoting enhanced heat transfer rates and consequently shortening the melting duration. This investigation systematically assessed the influence of three selected inlet temperatures, namely 358 K, 368 K, and 373 K, and the corresponding outcomes are summarized comprehensively in Table 8.

The results indicate that the highest inlet temperature, 373 K, produced the most rapid melting, achieving complete PCM melting within 237.3 minutes. This represents a notable improvement of approximately 50.50% compared to the baseline condition, which required 479.4 minutes. Similarly, the intermediate inlet temperature (368 K) also significantly enhanced melting performance, completing the process within 308.7 minutes—equivalent to a 35.61% reduction compared to the baseline scenario. Conversely, the lower inlet temperature of 358 K resulted in a substantially prolonged melting period, yielding a performance markedly inferior to the baseline, with an error percentage exceeding 300%.

The findings clearly demonstrate that the optimal selection of HTF inlet temperature critically influences PCM melting efficiency, confirming that higher temperatures, such as 373 K, substantially enhance thermal energy storage performance through accelerated melting processes.

Table 8: The results for various inlet temperatures.

Inlet Temperature	Melting Completion Time	Improvement Percentage
Baseline	479.4 minutes	-
358 K	1950 minutes	-306.76 %
368 K	308.7 minutes	35.61 %
373 K	237.3 minutes	50.50 %

Figure 9(a) clearly demonstrates the significant influence of increasing the inlet temperature on the melting time of the phase change material (PCM). As the inlet temperature rises, the time required for complete melting decreases considerably. This effect is attributed to the increased temperature gradient between the heat transfer fluid (HTF) and the PCM, which intensifies the heat transfer rate. The baseline configuration, with an inlet temperature of 363 K, exhibits the slowest melting rate due to the relatively low thermal driving force. In contrast, inlet temperatures of 368 K and 373 K facilitate much faster-melting rates, substantially reducing the time to achieve complete melting. These results highlight the critical role of selecting an optimal inlet temperature to enhance the efficiency of latent heat thermal energy storage (LHTES) systems.

Figure 9 (b) provides a comparative assessment of temperature profiles for inlet temperatures of 368 K, 373 K, and the baseline case. The temperature curves reveal a sharp rise during the initial melting phase, reflecting rapid heat absorption and a strong thermal response. As the melting progresses and the PCM approaches the phase transition point, the rate of temperature increase becomes more gradual, indicating the formation of a partially melted region where conduction and convection interact more dynamically [12]. This trend confirms that higher inlet temperatures not only accelerate the melting process but also contribute to maintaining an efficient thermal gradient, thereby optimizing the overall performance of the LHTES system.

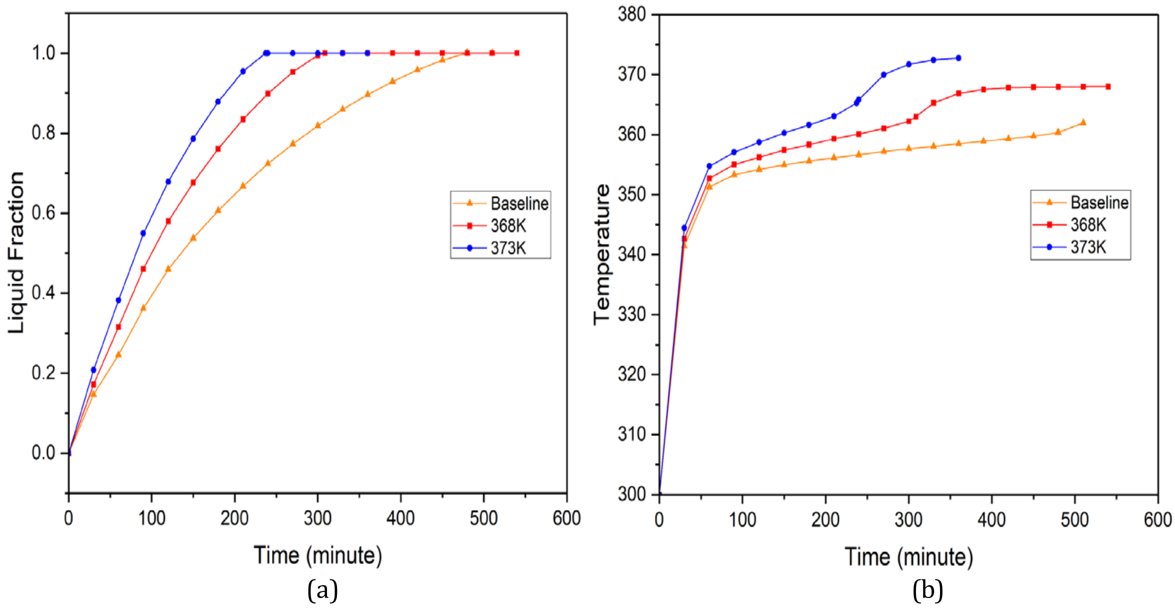


Figure 9: (a) Comparison liquid fraction of different inlet temperatures, (b) Comparison temperature of different inlet temperatures.

Figure 10 illustrates the melting progression of the phase change material (PCM) at three different inlet temperatures (358 K, 368 K, and 373 K) across four time intervals (60, 120, 180, and 240 minutes). The liquid fraction is represented on a color scale, where blue denotes the solid state (liquid fraction = 0) and red signifies complete melting (liquid fraction = 1).

At the lowest inlet temperature of 358 K, the melting process is notably sluggish and remains incomplete even after 240 minutes. This is primarily due to the limited temperature gradient between the heat transfer fluid (HTF) and the PCM, resulting in insufficient heat transfer to induce a complete phase change. As a consequence, the PCM predominantly remains in the solid state, highlighting the inadequacy of the thermal driving force at this temperature level.

In contrast, the intermediate inlet temperature of 368 K shows significant improvement in melting performance. By the 240-minute mark, the PCM is observed to be nearing full melting, with complete melting achieved at approximately 308.7 minutes. This represents a substantial enhancement compared to the lower temperature scenario, reflecting the beneficial effect of increased thermal gradient on heat transfer efficiency.

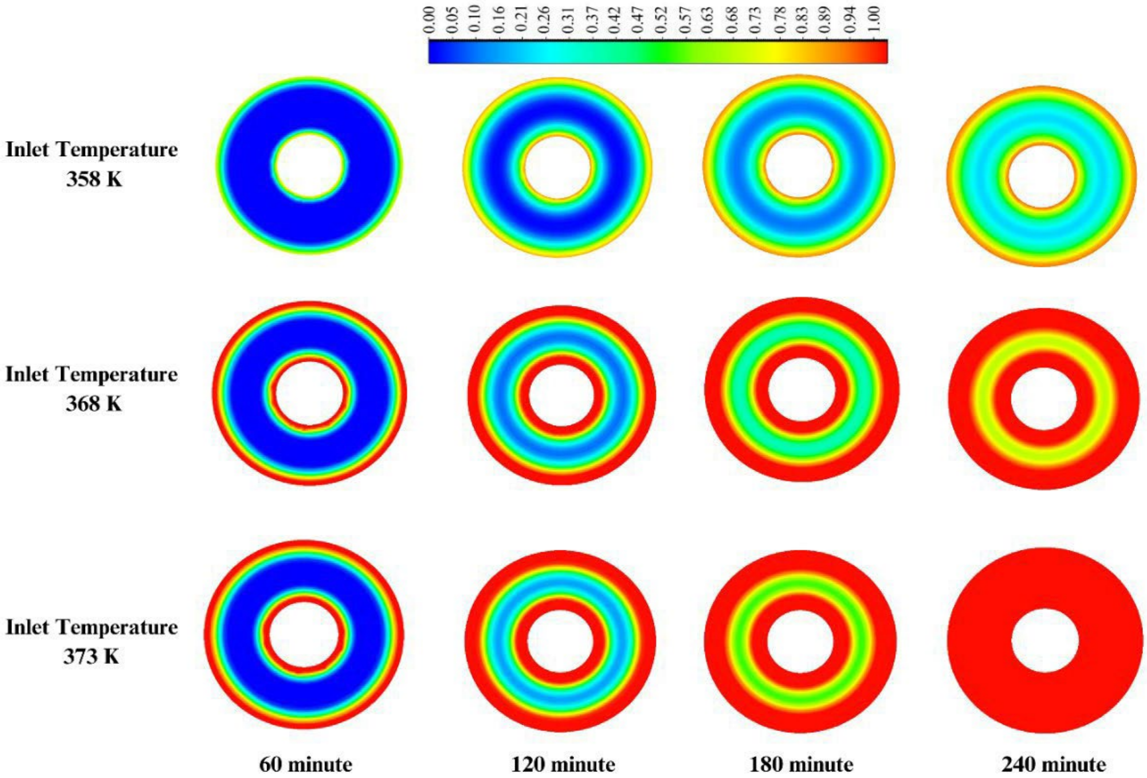


Figure 10: Contour of inlet temperature parameter study.

The most favorable outcome is observed at the highest inlet temperature of 373 K, where melting proceeds rapidly and is completed in less than 240 minutes. The contour plot for this case shows a fully red profile at the 240-minute interval, indicating a liquid fraction value of 1 and confirming that the PCM has completely transitioned to the liquid phase.

These findings clearly demonstrate the pivotal role of inlet temperature optimization in enhancing the thermal performance of latent heat thermal energy storage (LHTES) systems. Higher inlet temperatures not only expedite the melting process but also ensure thorough phase change, thereby significantly improving the overall efficiency and reliability of the thermal storage system.

3.2 Combination Parameter Setting

The optimization of latent heat thermal energy storage (LHTES) performance requires a comprehensive approach that considers key operational parameters, including mass flow rate, flow direction, and inlet temperature. In this study, each parameter was systematically analyzed independently to identify the optimal settings that yield the highest melting efficiency. Subsequently, the most effective values for each parameter were integrated into a single configuration, allowing for a holistic assessment of performance improvements. The selected combination, as outlined in Table 9, incorporates the best-performing values for mass flow rate, flow direction, and inlet temperature, ensuring that the collective impact of optimized settings is fully realized.

The simulation results demonstrate that this integrated optimization strategy markedly enhances PCM melting performance when compared to the baseline configuration. As shown in Table 10, the optimized combination successfully reduced the melting time to 232.8 minutes, reflecting a substantial improvement of 51.44% over the baseline scenario. These findings underscore the significance of adopting a multidimensional optimization approach, as the synergistic effects of combining individually optimized parameters result in superior thermal performance.

This study clearly demonstrates that while optimizing each parameter independently contributes to improved PCM melting efficiency, the integration of the optimal settings yields even greater enhancements. The results affirm the critical importance of parameter optimization and integration in advancing the operational efficiency and reliability of LHTES systems.

Table 9: Selection of the highest result of each parameter.

Combination Parameter	Melting Completion Time
Mass Flow Rate – 0.5 kg/s	463.8 minutes
Flow Direction – Inner Opposite	468.9 minutes
Inlet Temperature – 373 K	237.3 minutes

Table 10: Improvement percentage result.

Parameter	Temperature	Melting Time Completion	Improvement Percentage
Baseline	360.34 K	479.4 minutes	-
Combination Parameter	365.10 K	232.8 minutes	51.44 %

Figure 11 provides a comparative analysis between the optimized parameter combination result, the result for an inlet temperature of 373 K, and the baseline scenario. The inlet temperature of 373 K is specifically highlighted, as it exhibited the highest performance among individual parameter optimization studies. The comparison clearly demonstrates that the optimized combination of parameters yields superior melting performance, achieving complete phase change in 232.8 minutes, compared to 237.3 minutes when utilizing the 373 K inlet temperature alone.

This improvement of 1.90% may appear modest, yet it represents a crucial enhancement when striving to maximize the efficiency of latent heat thermal energy storage (LHTES) systems. The findings affirm the value of integrating optimized parameters to achieve cumulative performance gains, thereby advancing the overall thermal management and operational efficiency of the system. This integrated approach to parameter optimization underscores its critical importance in the pursuit of more efficient and reliable LHTES solutions.

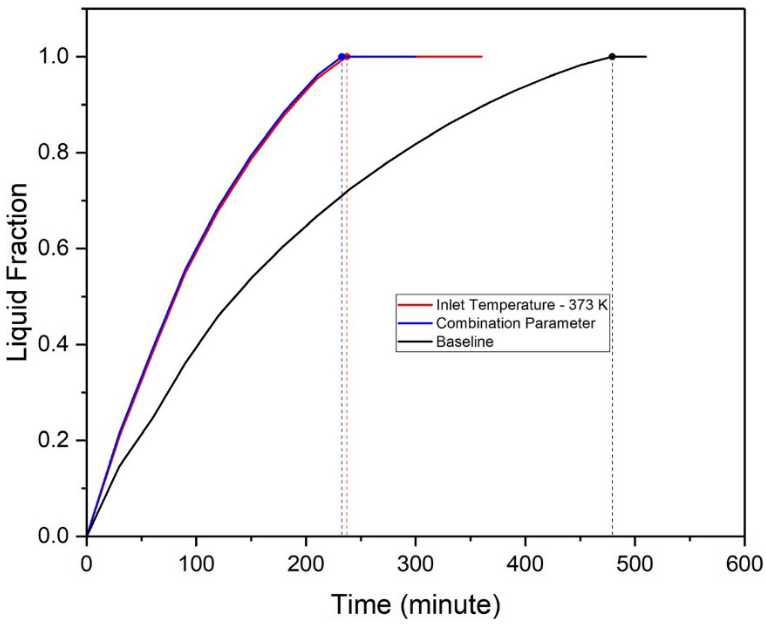


Figure 11: Comparison result of combination parameter.

4. CONCLUSION

This study systematically examined the performance of latent heat thermal energy storage (LHTES) utilizing a triplex tube heat exchanger, with paraffin wax RT82 as the phase change material (PCM) and copper as the tube material. Numerical simulations were conducted using ANSYS Fluent to investigate the effects of key operational parameters, including mass flow rate, flow direction, and inlet temperature, on the melting behavior of the PCM.

The optimized mass flow rate of 0.5 kg/s significantly reduced the melting time to 463.8 minutes, representing a 3.25% improvement compared to the baseline scenario. Similarly, the inner opposite flow direction configuration decreased the melting time to 468.9 minutes, yielding a performance enhancement of 2.19%. Among all the parameters examined, the inlet temperature of 373 K exhibited the most substantial impact, achieving complete melting in just 237.3 minutes, reflecting a remarkable 50.50% improvement over the baseline.

Combining the optimized parameters yielded the most favorable outcome, with the PCM achieving complete melting in 232.8 minutes, representing a 51.44% reduction from the baseline. In contrast, an inlet temperature of 358 K failed to induce complete melting, underscoring the critical importance of maintaining a sufficient thermal driving force to ensure efficient heat transfer.

These findings emphasize the necessity of optimizing operational parameters to maximize the efficiency of LHTES systems, providing valuable insights for advancing sustainable energy storage solutions capable of balancing renewable energy demand and supply.

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