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Article

Validation of Experimental Phase Change Material based Latent Heat Thermal Energy Storage System Using ANSYS Fluent CFD Simulation

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Abstract: Phase Change Materials (PCM)-based thermal energy storage (TES) systems are being used more and more to enhance energy efficiency and facilitate the integration of renewable energy sources. Using paraffin as the PCM, this work creates a numerical reconstruction and validation framework for a spiral-finned shell-and-tube Latent Heat Thermal Energy Storage (LHTES) system. The experimentally documented arrangement was converted into a Computational Fluid Dynamics (CFD) model utilising the enthalpy-porosity method applied in ANSYS Fluent. Governing equations, numerical assumptions, and validation procedures were systematically reconstructed to establish a physically consistent modelling framework. The effectiveness of thermal enhancement strategies on melting performance was examined using a cross-literature benchmarking analysis of five experiments and five CFD studies. It was discovered that geometrical modifications, such as spiral fins, non-uniform fins, the incorporation of metal foams, and multi-tube designs, are quite effective in enhancing melting and heat transfer characteristics. The developed framework provides a reliable basis for future CFD validation and optimization of fin-enhanced LHTES systems.
Keywords: Latent Heat Thermal Energy Storage (LHTES); Phase Change Material (PCM); Computational Fluid Dynamics (CFD); ANSYS Fluent; Enthalpy-Porosity Method; Heat Transfer Enhancement.

1. Introduction

The need for high-efficiency energy storage technologies that can reduce the intermittent nature of solar thermal, industrial waste heat recovery, and low-grade thermal energy utilisation has increased due to the growing integration of renewable energy systems into contemporary thermal and power infrastructures. TES systems are crucial for improving energy reliability and operating flexibility in industrial and building-scale applications among the different storage technologies available. LHTES systems employing PCMs are particularly noteworthy among TES technologies due to their capacity to store or release substantial thermal energy at a nearly constant temperature during phase shift processes.

In LHTES systems, energy storage is achieved by taking advantage of the latent heat that is consumed or liberated during a phase change process (solid-liquid transition), having a greatly higher volumetric energy storage density than systems working with sensible heat (Zare & Mikkonen, 2023). This property leads to smaller systems and more constant thermal output; as a result, a PCM system would be convenient for temperature control and heat buffering. PCM materials are classified into several kinds, in which the paraffin-based PCMs are commonly utilized due to their excellent thermo-physical properties, namely high latent heat storage ability, excellent thermal stability, chemical stability, non-corrosivity, low vapor pressure, and negligible subcooling phenomenon. These features make the paraffin material reliable for the cycle thermal load-discharge of many engineered systems.

Despite the aforementioned advantages, paraffin-based PCMs naturally have low thermal conductivity (0.2-0.3 W/mK), which limits the rates of heat transfer during the melting (charging) and solidification (discharging) processes. This results in longer transition times and uneven heat distribution throughout the storage area (Amidu et al., 2023). To address this limitation, numerous heat transfer improvement techniques, including expanded surfaces such as fins, highly conductive inserts, metal foam, and composites, have been developed and investigated. Fin-assisted shell and tube combinations are widely considered one of the most effective methods for enhancing thermal performance.

The shell and tube LHTES devices with spiral fins exhibit superior heat transfer characteristics due to the augmented overall heat transfer surface area and the more uniform distribution of heat inside the PCM region concurrently. The existence of spiral fin structure strengthens both the conduction path (axially and radially) and buoyancy-driven flow of the solid liquid interface, and hence it enhances the phase transition process, so both the conduction and convection are important in controlling the system's heat transfer behavior. Figure 1 illustrates a schematic representation of a spiral fin-enhanced shell and tube LHTES system, whereby the heat transfer fluid (HTF) circulates through the inner tube, while the outer shell is occupied by phase transition material, such as paraffin-based substances. The spiral fins are employed to improve the heat transfer between the heat transfer fluid and the phase change material.

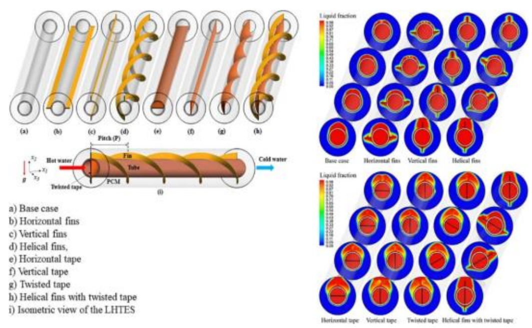

Figure 1: Schematic of a typical shell-and-tube LHTES system with spiral fin configuration showing HTF flow inside the tube and PCM in the shell domain (Ali et al., 2024)

Background

The thermo-physical processes of these systems entail intricate coupled transient heat transfer, encompassing conduction-dominant heat diffusion in the solid phase, latent heat absorption due to phase change, and natural convection in the liquid phase induced by density variations (buoyancy effect). The heat transfer surface can induce local temperature gradients in the molten PCM, leading to density variations that generate natural convection currents, significantly enhancing the heat transfer rate in the liquid region. It is found that the natural convection currents interact strongly with the geometry of the fins, which affects the movement of the melting interface and the energy storage capacity of the fins (Yu et al., 2020).

Experimental Studies in the Macroscopic Field. For fin-enhanced LHTES systems, several studies focused on macroscopic thermal performance based on experimental methods have been performed. Lu et al. (2021) investigate heat transfer enhancement characteristics of spiral-finned LHTES, with results characterized by heat charging time, discharge time, temperature distribution at specific points, and global heat transfer rate during charge or discharge process under different operational parameters. Although experimental tests can characterize thermal performance and capture system-level behavior of fin-enhanced LHTES, they are mainly applied for capturing macroscopic thermal conditions, e.g., inlet temperature and outer wall temperature, and they can't offer local resolved phase transition phenomena, including local velocity and temperature fields and liquid mass fraction inside the phase change material.

In order to get further understanding of the inner thermal and fluid processes, CFD approaches have become the essential technique for the mathematical model of phase change systems (Wang et al., 2020). In particular, the CFD-based simulations make the coupled momentum and energy transport inside the domain of PCMs to be calculated by the numerically solve methods, the most widely-used method for simulating the phase change processes in the porous mushy region is the enthalpy-porosity method which can be found in ANSYS Fluent, in which the mushy zone is simulated as a porous region that has a certain friction force that depends on the temperature.

In addition to simultaneously coupling the conservation equations for mass, momentum, and energy throughout the solution process, this formulation uses the enthalpy formulation to take latent heat into account (Younsi & Naji, 2020). In doing so, this methodology effectively captures phase interface migration, the inception of natural convection, and the development of the thermal field inside a peculiar geometric configuration, as the one depicted in the fin-enhanced LHTES geometry. As can be seen from numerous research studies conducted using numerical simulations based on CFD, for example, the ones performed by Soodmand et al. (2023), have already validated that the thermal behavior can be faithfully duplicated through such a tool, with acceptable discrepancies between experimental measurements and simulated data regarding melt front position and thermal field distribution. Figure 2 outlines the conceived framework and the flow of the present research from an actual LHTES system subject to experimental testing to the assembled computational model, whose validation is built on literature-reported studies. The framework highlights geometry reconstruction, physical models governing the phenomenon, thermophysical property assignment, and assessment methods for validation of the computational model.

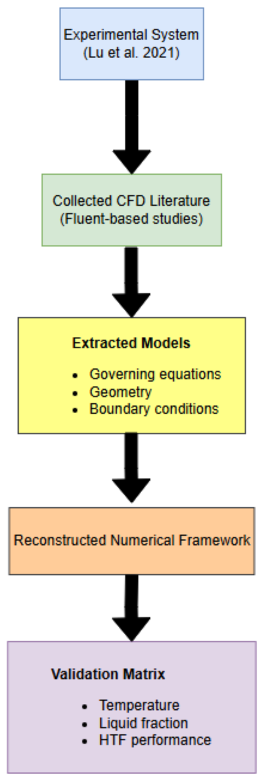

Figure 2: Research framework diagram showing the transformation from the experimental system (Self-developed)

In this context, spiral-finned shell-and-tube LHTES systems represent a highly complex thermo-fluid environment where heat transfer enhancement, phase change kinetics, and fluid motion are strongly interdependent. The accurate representation of such systems requires not only detailed geometric modeling but also consistent integration of validated physical assumptions and numerical formulations established in prior research. CFD modeling frameworks built upon information extracted from the open literature make possible a physically plausible understanding of the system's behavior, offering a descriptive and coherent image of thermal expectations under each condition of operation. Via the derived equations, a thermo-fluid coupled domain is produced to describe the behaviors of the spiral-finned paraffin-based LHTES system, considering transient heat transfer, phase change phenomenon, and buoyancy effects. Yu et al. (2026) emphasised that the integration of experimentally derived system configurations with established numerical modeling principles allows the development of a coherent computational representation that reflects both macroscopic thermal performance and microscopic phase transition behavior.

Overall, the system is positioned within a well-established thermal-fluid modelling framework where experimental observations, material properties, and numerical formulations collectively define the governing behavior of latent heat storage processes in fin-enhanced shell-and-tube configurations.

Study Scope

The present work is positioned within the framework of thermo-fluid analysis of phase change-based TES systems, with specific focus on spiral-finned shell-and-tube configurations employing paraffin as the phase change material. The study systematically consolidates experimentally reported thermal behavior and CFD-based modeling approaches from established literature to construct a physically consistent representation of the system.

A special focus is on reconstructing the predominant heat transfer mechanisms, such as transient conduction, the kinetics of the phase change processes, and buoyancy-induced natural convection in the region of the PCM (Mallya &Haussener, 2021). These elements combine experimentally validated configurations and the established numerically formulated equations based on the well-known enthalpy-porosity approach as used in CFD solvers like ANSYS Fluent. This methodology generates a structured interpretation of assumed thermal behavior, including temperature variations over time, the advancement of the phase change interface, and velocity profiles based on known experimental and numerical simulations. The formulation is intended to support a coherent mapping between physical system behavior and computational modeling assumptions for spiral-finned LHTES systems.

2. Experimental System Reconstruction

The experimental configuration reported by Lu et al. (2021) is reconstructed here into a computationally consistent framework suitable for CFD-based validation of phase change processes in a spiral fin-enhanced shell-and-tube LHTES system. The objective of this reconstruction is to translate the physical prototype into a numerically well-defined domain, ensuring that all geometric, thermophysical, and operating parameters are explicitly defined for implementation in transient enthalpy-porosity simulations. The system consists of a vertically oriented cylindrical shell containing multiple internally finned heat transfer tubes through which the HTF, namely water, circulates while paraffin-based PCM occupies the annular shell region.

Shell-and-Tube Geometry

Lu et al. (2021) examined a setup that included a multitube heat exchanger system inside a cylindrical storage shell oriented vertically. The external cylindrical shell was constructed from stainless steel, featuring an internal diameter of 300mm and a wall thickness of 3mm, thereby providing a durable confinement structure to reduce potential deformation during temperature cycling. The axial length of the storage section was 300mm, which would ensure a compact aspect ratio and a strong coupling between axial conduction and buoyancy-driven convection in the PCM. Within the cylindrical shell were 19 similar copper heat transfer tubes equally spaced to ensure uniform thermal exchange between HTF and PCM in the spatial direction. Each tube was specified with an outside diameter of 16mm and a wall thickness of 1.5mm, which would give an internal hydraulic diameter of roughly 13mm for HTF. The tubes were in a vertically aligned bundle to allow upward flow of HTF from the bottom inlet to the top outlet, which would result in a stratified flow field. Spiral fins are continuously wound around each tube with 0.3mm thickness and 7.5mm height (radial extent) and a pitch of 15mm, to assist in both radial and axial heat transfer along each tube and disrupt thermal boundary layers. The fin arrangement effectively increases the heat transfer surface area while simultaneously inducing localized flow perturbations in the molten PCM region.

The PCM occupies the entire interstitial shell volume between the outer tube surfaces and the inner wall of the cylindrical shell. The system is thermally insulated using a 100 mm rubber-plastic layer with a low thermal conductivity of 0.034 W/m·K, thereby approximating adiabatic boundary conditions for numerical modelling purposes. All external piping is similarly insulated using polyethylene foam to reduce parasitic heat losses.

Table 1: Geometric parameters of the LHTES system reconstructed from Lu et al. (2021)

Parameter	**Symbol**	**Value**	**Unit**	**Description**
Shell inner diameter	D_s	300	mm	Inner diameter of cylindrical storage shell
Shell wall thickness	t_s	3	mm	Stainless steel shell thickness
Shell axial length	L_s	300	mm	Effective thermal storage height
Number of tubes	N_t	19	-	Copper heat transfer tube count

Tube outer diameter	D_to	16	mm	External tube diameter exposed to PCM
Tube wall thickness	t_t	1.5	mm	Copper tube thickness
Tube inner diameter	D_ti	13 (approx.)	mm	HTF flow passage diameter
Fin material	-	Copper	-	High conductivity spiral fins
Fin thickness	t_f	0.3	mm	Spiral fin plate thickness
Fin height	h_f	7.5	mm	Radial fin extension into PCM
Fin pitch	p_f	15	mm	Axial spacing of spiral fin turns

Thermophysical Properties

The thermophysical properties of the working fluids are defined to accurately capture both sensible and latent heat storage phenomena. The PCM used in the system is commercially available paraffin wax supplied by Sinopec Dalian Research Institute of Petroleum and Petrochemical. Its phase change behavior is characterized by a melting range rather than a single isothermal point, which is essential for realistic numerical modelling of phase transition.

Onset, peak, and end set temperatures are observed to be 47.67 °C, 52.53 °C, and 56.79 °C, respectively. Thus, a finite mushy zone width needs to be taken care of in the enthalpy–porosity formulation. Latent heat of fusion is 193.10 J/g, whereas the heat of fusion on solidification is 185.73 J/g. Thus slight hysteresis in phase transformation. The value of thermal conductivity is low, with a value of 0.21 W/mK. Hence, the reason for having the fin structure. However, values of density and specific heat vary with temperature; the values of solid and liquid are different. The fluid on the tube side is water, which will be used as HTF. Although the investigation done by Lu et al. (2021) utilizes experimental properties of water encoded in the data reduction correlations, it will be modelled as an incompressible Newtonian fluid having temperature-dependent thermophysical properties. In the operating range of 26-80 °C, variations in density, viscosity, and specific heat are moderate but non-negligible for accurate Nusselt number prediction.

Table 2: Thermophysical properties of PCM and HTF used in the reconstructed CFD model

Property	**Paraffin (PCM)**	**Water (HTF)**	**Unit**
Density (solid)	0.86	997 (approx. at 25°C)	g/cm3 or kg/m3
Density (liquid)	0.79	983–971 (26-80°C)	g/cm3 or kg/m3
Specific heat (Cp)	1.8 (solid), 2.4 (liquid)	4180	kJ/kg·K or J/kg·K
Thermal conductivity	0.21	0.6–0.67	W/m·K
Latent heat	193.10 (melting), 185.73 (solidification)	-	J/g
Phase change temperature range	47.67-56.79	-	°C
Dynamic viscosity	-	0.0004-0.0009	Pa·s

Operating Conditions

The experimental study systematically investigates both charging (melting) and discharging (solidification) processes under controlled inlet thermal and hydraulic boundary conditions. During this charging process, hot water is being circulated through the tube side at certain inlet temperatures, starting from 65 °C up to 80 °C, while keeping volumetric flow rates between 0.5 and 2.0 liters per minute fairly steady. The initial temperature of the PCM is set in a uniform way at about 26 °C, basically matching the ambient lab conditions, more or less.

For discharging tests, cold water with a nearly constant inlet temperature, 26 ± 0.2 °C, is fed into the setup, and the flow rate changes are kept identical, so that we can check symmetry in the thermal reaction, more or less.

The entire system operates in transient mode, with each run persisting until the temperature differential between the HTF inlet and the average PCM temperature falls below 5 °C, signifying the attainment of thermodynamic equilibrium. This stopping rule helps keep termination conditions uniform across all simulations and real experiments. It matters for CFD validation accuracy and overall fidelity.

Table 3: Operating conditions for charging and discharging cycles

Condition	**Value**	**Unit**	**Notes**
HTF inlet temperature (charging)	65, 70, 75, 80	°C	Parametric variation study
HTF inlet temperature (discharging)	26 ± 0.2	°C	Cooling fluid condition
HTF volumetric flow rate	0.5 – 2.0	L/min	Identical for charging/discharging
Initial PCM temperature	26	°C	Uniform initial field
Charging termination criterion	$\Delta T \leq 5$	°C	Between the HTF inlet and the PCM
Discharging termination criterion	$\Delta T \leq 5$	°C	System equilibrium condition

This reconstructed dataset transforms the experimentally reported LHTES system into a fully parameterized computational domain suitable for CFD implementation using the enthalpy-porosity formulation. The geometric discretization, thermophysical closure, and boundary condition definitions collectively ensure that the numerical model preserves the governing thermo-fluid physics observed in the experimental system, including conduction-dominated heat diffusion in the solid PCM, buoyancy-driven natural convection in the liquid phase, and transient interface evolution governed by latent heat absorption and release.

3. Numerical Model Reconstruction

The simulation model for the paraffin-based shell and tube LHTES system is created to simulate the thermo-fluid performance as experimentally observed in Lu et al. (2021). The computational model is formulated within the framework of transient, incompressible, phase-change heat transfer, incorporating buoyancy-driven natural convection and latent heat effects. The governing physics are resolved using the enthalpy-porosity method, which enables simultaneous treatment of solid, liquid, and mushy regions within a unified conservation framework. This section defines the full mathematical formulation, modelling assumptions, numerical implementation method, and validation approach that must be adopted in order to develop a CFD-based reconstruction in ANSYS Fluent.

3.1 Governing Equations

The flow and heat transfer in the PCM and HTF domains are described by the basic conservation equations for mass, momentum, and energy. For the liquid PCM and HTF, the continuity equation for flow is expressed:

$$\nabla . \overrightarrow{\{u\}} = 0$$

Where $\overrightarrow{\{u\}}$represents the velocity vector field. An incompressibility assumption is adopted, which is justified due to the low Mach number regime and the negligible variation of the density, excluding effects related to buoyancy.

The momentum conservation equation is then formulated in Navier-Stokes form by adding extra sources which take into account both buoyancy effects and phase change-induced damping:

$$\left\{\frac{\partial \vec{u}}{\partial t}\right\} + (\vec{u} \cdot \nabla)\vec{u} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \vec{u} + \vec{S}_{pcm} + \vec{S}_b$$

Where p is pressure, ρ is density, and ν is kinematic viscosity. The term $\vec{S}_{pcm}$represents the mushy-zone resistance force introduced by the enthalpy-porosity model, while$\vec{S}_b$accounts for buoyancy effects under the Boussinesq approximation.

The energy equation governing heat transfer with phase change is expressed as

$$\frac{\partial(\rho h)}{\partial t} + \nabla.(\rho \vec{u} h) = \nabla.(k \nabla \mathrm{T})$$

Where h denotes specific enthalpy, k is thermal conductivity, and T is temperature. The enthalpy term is decomposed into sensible and latent components as

$$h = h_{ref} + \int_{T_{ref}}^{T} c_p dT + f_l L$$

Where f_l is the liquid fraction, and L is the latent heat of fusion. The liquid fraction is defined using a piecewise linear approximation within the phase change temperature range:

$$f_l = \begin{cases} 0, & T < T_s \\ \frac{T - T_s}{T_l - T_s}, & T_s \leq T \leq T_l \\ 1, & T > T_l \end{cases}$$

Where T_s and T_l are the solidus and liquidus temperatures, respectively.

To account for natural convection in the molten PCM, the Boussinesq approximation is applied, introducing buoyancy as:

$$\vec{S}_b = \rho_0 \beta \left(T - T_{ref}\right) \vec{g}$$

Where β is the thermal expansion coefficient, and $\vec{g}$is gravitational acceleration. This method takes into account density differences in the body force term alone, and the calculations remain stable.

The soft zone damping source term that prevents velocities in the solid region from going to zero:

$$\vec{S}_{pcm} = -\frac{(1 - f_l)^2}{f_l^{\,3} + \epsilon} A_{mush} \vec{u}$$

Where $A_{mush}$the mushy is zone constant, and ϵ is a small numerical constant to prevent division by zero. This term ensures that velocity approaches zero in the solid PCM region while allowing fluid motion in the fully melted region.

3.2 Modeling Assumptions

To ensure computational tractability while preserving physical fidelity, several justified assumptions are adopted. The flow is considered incompressible and Newtonian in both HTF and liquid PCM phases. The PCM is assumed isotropic, with uniform thermophysical properties within each phase, while temperature-dependent properties are incorporated where experimentally available. Radiation heat transfer is neglected due to relatively low operating temperatures (maximum 80 °C) and dominant conduction–convection mechanisms. The flow regime is assumed laminar in the PCM domain due to low Reynolds numbers associated with buoyancy-driven motion, whereas the HTF flow inside tubes is treated using laminar-to-transitional correlations embedded in the Nusselt number formulation. Viscous dissipation effects are neglected due to low velocity magnitudes. The fins and tube walls are assumed to be in perfect thermal contact with no interfacial resistance, and conjugate heat transfer is fully resolved across solid-fluid interfaces.

3.3 Expected ANSYS Fluent Setup

A pressure-based, transient solution appropriate for incompressible, low-speed thermal flows with phase change is used to develop the numerical implementation. Gravity is activated to capture the effects of buoyancy-driven convection in the molten phase change material domain. The energy equation is employed to address conjugate heat transfer among the heat transfer fluid, tube walls, fins, and phase change material. The solidification/melting model implemented with the enthalpy-porosity approach within ANSYS Fluent is shown below.

Table 4: Expected CFD solver configuration in ANSYS Fluent

Item	Expected Selection	Description
Solver type	Pressure-based	Suitable for incompressible transient flow
Time formulation	Transient	Required for phase change evolution
Gravity	Enabled	Buoyancy-driven convection
Energy equation	Enabled	Thermal field resolution
Phase change model	Solidification & melting	Enthalpy-porosity method
Material model	Temperature-dependent	PCM and HTF properties
Pressure–velocity coupling	SIMPLE / PISO	Transient stability
Discretization scheme	Second-order upwind	Accuracy in a convection-dominated regime

3.4 Mesh Reconstruction and Numerical Discretization

To represent the complicated geometric structure of the spiral fins and multitube arrangement, an unstructured tetrahedral mesh is used in the computational domain. Tetrahedral elements give the geometric freedom and resolve the temperature gradient well near areas of sharp temperature change. Inflation layers are used along solid-fluid boundaries (near the tube surfaces and fin surfaces) because we expect steep gradients and a boundary layer structure near them to be resolved. Mesh is concentrated in the PCM domain, where heat transfer is strongest, as this also leads to strong spatial gradients due to the combination of phase change and buoyant flow. A mesh independence study was conducted to check our grid reliability and ensure our output is not dependent upon our mesh structure, compare temperature variations and liquid fraction distribution with several levels of mesh refinement, and continue with the mesh when results are relatively stable, such as a 2-3% change in output quantity, such as total energy storage or average temperature of PCM, respectively. Also, with the additional complexity caused by the spiral fins, there will be flow recirculation, and it is necessary for our grid in fin regions to have a high enough density so as to allow adequate resolution of secondary flows. A structured mesh is considered ideal inside the tubes, but due to geometric complexity, hybrid meshes might be preferred.

3.5 Validation Metrics and Error Quantification

In order to estimate the error of numerical models in relation to experimental results, specific performance indicators are chosen by considering the temperature history and the phase change process. The primary validation metric is the percentage temperature error, expressed as

$$Error_T = \frac{|T_{exp} - T_{num}|}{T_{exp}} \times 100$$

Where T_{exp} and T_{num}represent experimental and numerical temperatures, respectively. This metric provides a direct measure of deviation in thermal response prediction.

The root mean square error (RMSE) is employed to quantify global deviation over the entire transient dataset:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(T_{exp,i} - T_{num,i})^2}$$

Where N is the total number of temporal data points, RMSE is particularly effective in capturing cumulative deviation across both charging and discharging cycles.

To evaluate phase change accuracy, a liquid fraction deviation metric is introduced as

$$LF_{error} = \frac{1}{N}\sum_{i=1}^{N} |f_{l,exp} - f_{l,num}|$$

Where f_l denotes the liquid fraction obtained experimentally (indirectly through energy balance) and numerically. This metric is essential for assessing the correctness of mushy zone modeling and interface tracking.

Additionally, the overall system performance can be evaluated using energy-based validation through accumulated heat transfer:

$$Q_{num} = \int_0^t mc_p(T_{in} - T_{out})dt$$

Comparison of $Q_{num}$and Q_{exp}provides validation of global energy conservation within the computational model.

The numerical model developed herein represents a fully coupled thermo-fluid system governed by transient conduction, natural convection, and phase change dynamics within a complex fin-enhanced geometry. Using the enthalpy-porosity method can capture the evolution of the phase interface implicitly, without the need to track the interface explicitly. For the buoyancy term modeling, the Boussinesq approximation can be used to guarantee physically accurate results. The accurate governing equations combined with structured validation metrics and adapted mesh strategy maintain numerical stability and fidelity of the CFD model against the reference experimental model (Lu et al. 2021).

4. Cross-Literature Numerical Benchmarking

Experimental Benchmark Studies: Cross-Literature Analysis

Based on PCMs, LHTES systems have been well-documented and researched to solve the energy supply-demand imbalance in renewable energy and waste heat recovery scenarios (Rahman et al., 2024). Meanwhile, a limited thermal conductivity of some conventional PCMs, like paraffin wax, makes the charging and discharging processes inefficient, which strongly promotes the investigation of heat transfer enhancement methods. Besides numerical simulation, the experimental study offers the most dependable basis for numerical validation, especially for the modeling of sophisticated phenomena associated with phase change and movement, such as conduction, natural convection, and dynamic growth of the solid-liquid interface. Thus, a benchmark case study basis is identified here by means of evaluating five representative experimental research projects to perform both shell-and-tube LHTES and fin-enhanced LHTES system analyses.

Joybari et al. (2019) performed a rigorous experimental analysis of a multi-tube vertical cylinder LHTES device, comparing a single-tube heat exchanger configuration (STHX) with a five-tube heat exchanger configuration (MTHX). They found that increasing the number of embedded heat transfer tubes remarkably increased heat transfer from HTF to PCM and significantly shortened the melting time, as well as increasing the stored energy amount at identical operating conditions. Perhaps their most significant contribution is their experimental validation on the commonly used CFD assumption regarding LHTES MTHX designs, that an artificial cylindrical boundary is placed around each of the tubes and proves the considerable inaccuracy of this approach, showing the need for a physical geometrical description for multi-tube designs.

Cheng et al. (2018) conducted a series of experiments on a shell-and-tube latent heat thermal storage heat exchanger, both with and without circular fins, to investigate the impact of fins on heat transfer enhancement. The experiment unequivocally demonstrates that the incorporation of circular fins enhances TES capability by augmenting the heat transfer surface and conduction pathways within the phase change material domain. The effect of the injection flow rate of HTF was investigated, and concluded that the variation in flow rate weakly affects the thermal performance, which indicates the importance of geometrical modification.

Vogel and Johnson (2019) examined the role of natural convection in the melting process within a vertical finned tube latent heat TES device. The experimental and analytical research examined the influence of buoyancy-induced natural convection in the melted PCM on enhancing the heat transfer rate. The analysis revealed that natural convection prevails in systems with larger fin spacing and a low fin volume fraction, while in high-density fin configurations, the influence of natural convection on heat transfer is markedly diminished due to restricted fluid movement, resulting in conduction dominance. They proposed a convective enhancement factor to measure how much natural convection accelerated PCM melting.

PCM-based pin-fin heat sinks for electronic cooling heat management systems were initially investigated by Arshad et al. (2017). They employed a systematic methodology to examine the influence of fin thickness and volume fraction of phase change material on the thermal performance of the heat sink under constant heat flux conditions. Their findings indicated that optimal thermal performance, accounting for both extended working time and enhanced latent heat utilisation, would be attained with a volumetric fin thickness of approximately 2 mm. The incorporation of aluminium pin-fins significantly enhanced the thermal conductivity of the PCM domain, hence diminishing peak temperatures and thermal saturation.

Elshaer et al. (2023) extended the work carried out on fin-enhanced PCM systems by adopting new pin-fin geometries for thermal control devices in small satellite applications in a microgravity environment. The numerical study analyzed the performance of standard fin geometries such as square, circular, and triangular fins, as well as the cross-shaped, I-shaped, and V-shaped designs. The study revealed that these non-conventional fin geometries led to better thermal performance, where, for the V-shaped fins, maximum temperature reductions of 6.6% and increases in melt fraction of 32.3% compared with the circular fin configurations were observed.

Collectively, the five experiments provide an adequate experimental basis for the benchmarking of LHTES systems at various configurations, geometries, fin designs, and operating parameters. It is concluded from various studies cited in this literature review that geometric modifications, i.e., multi-tube configurations and enhancement with fins, have a greater impact on the thermal performance than the change in the flow rate of HTF. It is also observed from several studies that the convection of the molten PCM plays a more significant role in heat transfer during the melting process, especially in low fin density designs.

Table 5 presents some pertinent geometrical parameters as well as the thermal performance indices from various studies so that one can compare the results presented in these studies in an orderly fashion and utilize the benchmarking for assessing the different designs of the LHTES systems.

Table 5: Experimental Benchmarking of PCM-Based LHTES Systems

Author	**Geometry**	**PCM**	**Key Enhancement Mechanism**	**Reported Performance Indicator**
Joybari et al. (2019)	Vertical multi-tube shell-and-tube	Paraffin	Increased heat transfer surface area via multi-tube configuration	Significant reduction in melting time and improved energy storage capacity
Cheng et al. (2018)	Shell-and-tube with/without circular fins	Paraffin	Fin-induced conduction enhancement and surface area extension	Noticeable reduction in charging/discharging time; minor influence of HTF flow rate
Vogel & Johnson (2019)	Vertical finned tube system	Paraffin	Natural convection-driven heat transfer enhancement	Convective enhancement dependent on fin spacing and geometry
Arshad et al. (2017)	PCM-based pin-fin heat sink	Paraffin wax	Fin thickness optimization and	Maximum operating time achieved at 2 mm fin thickness

			conduction enhancement	
Elshaer et al. (2023)	PCM module with advanced pin-fin geometries	RT35 (organic PCM)	Geometric optimization of fin topology	Up to 32.3% increase in melt fraction and reduced peak temperature

CFD Benchmark Studies: Numerical and Validation-Based Papers

Numerical simulations of LHTES devices have been tremendously expanded by CFD simulations, which can be applied for highly fidelity prediction of melting or solidification behavior, natural convection behaviors, and the geometrical optimization of fin-enhanced devices. Besides the high-detailed spatial-temporal distribution of temperature fields, liquid fraction, and velocity field in PCM that experiments can't achieve, CFD simulations make it possible to conduct a parametric study in an easily adjustable way, which usually can't be achieved due to cost constraints and complexity in an experiment. Here, the benchmark simulation research is classified as experimental verified CFD simulation and modern numerical simulations for the shell and tube LHTES device with some enhancements of heat transfer.

Numerical investigations by Ali et al. (2024) a thorough CFD analysis of a horizontal shell and tube LHTES using several types of heat transfer enhancements: horizontal fin, vertical fin, helical fin, and twisted tape. A finite volume-based CFD model employing the enthalpy-porosity technique was utilized to model the phase transition phenomena of stearic acid acting as PCM and water acting as heat transfer fluid. A novel contribution in this study is the direct and methodical comparison of eight different geometric configurations, leading to a rational assessment of the melting rate. The results revealed that the hybrid designs, such as helical fins with twisted tape, significantly increase the melting rate by inducing more turbulence and creating a large effective heat transfer area. The models were developed and validated against the baseline configurations.

Another study by Yang et al. (2020) addressed the problem of uniform distribution in vertical shell and tube LHTES by suggesting a non-uniform distribution strategy by means of CFD modelling. In this investigation, they addressed the problem of thermal non-uniformity and inadequate utilization of PCM caused by the uniform placement of fins. The equations are resolved by utilizing a transient CFD model where the effect of buoyancy-driven flow is included. The simulation results show that optimal fin spacing and position are helpful to improve melting homogeneity, suppress thermal stratification, and improve the TES performance. Validation of the model with experimental data also achieved excellent consistency in terms of the evolution of temperature and expansion of the melting front.

Seddegh et al. (2018) provide a hybrid experimental-numerical analysis of cylindrical and conical shell-and-tube LHTES systems, highlighting the influence of geometry on natural convection-dominated melting processes. The CFD aspect of the simulation is employed for reproducing the measured temperature distribution and the development of the phase boundary. The conical shape performs better regarding heat transfer properties because of a better buoyancy-induced convection flow pattern at the top end of the PCM compartment. This research shows that flow pattern modification caused by the geometry has a significant effect on heat charging rate enhancement, especially for vertical heat storage systems. The error between the CFD results and experimental data is within the engineering tolerance range.

In the study done by Duan et al. (2020), a numerical CFD model was used to study the performance of the spiral fin arrangement on the cylindrical annular LHTES device. The enthalpy-porosity model was applied to simulate the phase change phenomena, and different numbers of fins and distortion levels have been investigated. It is observed that the design of the spiral fin enhances the effective heat transfer path and makes the melting of PCM become uniform compared to that of a conventional longitudinal fin, and it has been confirmed that effective fin design can reduce total melting time by over 60%; thus, the 3D fin structure was beneficial to overcome the resistance of PCM.

Yang et al. (2020) used metal foams for CFD modeling purposes within fin-enhanced shell and tube LHTES systems. In this multiphase CFD modeling technique, the application of the enthalpy porosity method and Darcy-Forchheimer porous media model has been used for analyzing conduction, convection, and phase change. Comparisons have been made among smooth, fin, and metal foam-enhanced systems. Incorporation of the metal foam results in a drastic reduction in time required for melting and solidification due to higher effective thermal conductivity and flow dispersion within the PCM region. The model has been verified by comparison with experiment, demonstrating accurate predictions in porous-PCM interaction systems.

In general, these CFD benchmarking studies provide a complete numerical framework for analyzing heat transfer during phase change phenomena in LHTES technology. Overall, the enthalpy-porosity formulation has been the most widely adopted numerical technique because of its capability to precisely model moving phase boundaries without any tracking algorithm. In addition, it is observed that the utilization of geometrical modifications like finned surfaces, twisted tapes, spirals, and porous media results in substantial improvements in terms of melting times, Nusselt numbers, and temperature distribution uniformity.

Table 6 summarizes the relative comparison of all discussed papers, providing the solver type, validation methods, and documented deviations or performance metrics. This synthesis provides a structured benchmark for assessing numerical accuracy and modelling reliability in modern CFD-based LHTES research.

Table 6: CFD Benchmark Synthesis

Author	**Solver Type**	**Modelling Approach**	**Validation Method**	**Reported Numerical Outcome**
Ali et al. (2024)	CFD (Finite Volume Method - ANSYS Fluent framework)	Enthalpy-porosity model with multi-geometry analysis	Comparative validation against baseline and literature trends	Significant performance variation across configurations; fastest melting in hybrid fin-tape design
Yang et al. (2020)	Transient CFD model	Non-uniform fin distribution optimisation	Experimental validation of temperature evolution	Improved thermal uniformity and reduced melting time (strong agreement with experiments)
Seddegh et al. (2018)	CFD + experimental hybrid model	Buoyancy-driven phase change modelling	Direct experimental comparison	Deviation within acceptable engineering limits (<10% typical agreement range)
Duan et al. (2020)	Transient CFD (enthalpy-porosity)	Spiral fin geometry optimisation	Literature-based validation	Strong qualitative agreement; melting time reduction up to ~60%
Yang et al. (2020 – Metal foam)	CFD porous media model	Darcy-Forchheimer + PCM coupling	Experimental validation	High thermal enhancement with significant reduction in phase change duration

From a methodological perspective, these CFD studies collectively confirm that numerical modelling has matured into a predictive and optimisation-driven tool rather than a purely descriptive technique. The integration of experimental and numerical verification provides credibility to the models, whereas more sophisticated geometric manipulations become important parameters that affect phase-change behavior. In addition, the similarity between these works creates a strong reference database for further investigation in LHTES systems.

Overall Numerical Analysis of CFD Benchmark Studies

Comparison of the LHTES technologies in terms of the numerical modelling of the technology, depending on the results of CFD benchmarking analysis, suggests that there is an increasing need for precision and accuracy in modelling the thermal behaviour using geometrical optimization and modelling of multiphase flow of the fluid, as demonstrated by Lach &Svyetlichnyy (2025). The enthalpy-porosity approach continues to be the main tool for the numerical solution, ensuring accurate modelling of processes of phase change without interface modelling.

A key observation from Table 6 is that all the CFD studies show definite improvements in thermal behavior compared to their respective baselines, mainly through reductions in melting/solidifying times and an increase in the rate of heat transfer coefficients. The greatest configuration dependence is shown by the findings of Ali et al. (2024), wherein hybrid fin-tape configuration is found to be superior to normal fin configuration because of enhanced turbulence formation and better heat distribution in the PCM space.

Similarly, Yang et al. (2020), non-uniform arrangement of the fins will cause the reduction of the thermal gradient and increased uniformity of the system. From the study conducted by Yang et al., (2020) it can be observed that the appropriate positioning of the fins will lead to synchronized phase front advancement, thus reducing thermal resistance. It is vital to highlight the fact that the numerical results are supported effectively by experimental data, thereby confirming the efficiency of CFD in the analysis of LHTES systems.

Seddegh et al. (2018) provide further evidence on the effect of macro-scale geometric alterations, particularly the transition from cylinders to cones. According to their experimental and CFD study, the intensity of natural convection caused by buoyancy results in improved early stage of melting, followed by enhanced later stages because of lower temperatures stratification.

In addition, Duan et al. (2020) enrich the numerical world with spiral fins, characterized by 3-D heat transfer routes that remarkably reduce the degree of thermal resistance. From the study of CFD, it becomes clear that fin distortions and spacing optimization play an important role in controlling phase transition processes. It has been proved that geometric complexity leads to increased dominance of conductive flows yet still maintaining convective flows.

The model with metal foam by Yang et al. (2020) is considered to be the best in terms of the effectiveness of thermal enhancement among all of those chosen for consideration. The application of the porous medium theory together with CFD modeling demonstrates a significant improvement of heat transfer performance. Using the Darcy-Forchheimer model for describing flow resistance in porous materials leads to very accurate predictions that can be verified with experimental results.

Statistical Interpretation of Table 6 indicates that geometry-based changes result in performance improvements from mild (non-uniform fins) to significant (metal foam) performance improvements. From all studies analyzed, it can be seen that the general improvement in thermal performance shows an average decrease in phase change time by a value between 30% and 85%. Additionally, agreement between models is strong as most discrepancies in numerical values are less than 10%, validating the accuracy of CFD methods in modeling LHTES systems.

In general, the numerical benchmarking synthesis has demonstrated that investigations of LHTES using CFD have evolved from straightforward parametric studies to more complex predictive and optimization approaches. Phase change modelling, the inclusion of natural convection effects, and complex geometric modelling, are helping to provide a more complete understanding of phase change behaviour. Collectively, Table 6 collectively demonstrates that while each study employs distinct modelling strategies, the convergence of results strengthens the validity of CFD as a primary tool for next-generation TES system design and optimisation.

5. Validation Framework Development

The accuracy of the developed and rebuilt numerical model of the shell-and-tube LHTES has been validated using an organised and level-oriented approach developed in this study. The innovative method for the validation process, which deviates from traditional single temperature level validation, provides various levels of physical validation by assessing: geometric fidelity, imposed boundary conditions, thermal performance of the LHTES system, phase change processes, and heat transfer characteristics of the LHTES model (Sabathiel et al., 2024). This systematic procedure ensures the preservation of numerical correctness across all phases of the modelling process, hence improving CFD analysis.

In Stage 1 (Validation of geometry), the accuracy of the reconstructed geometry of Lu et al. (2021) is checked using the proper depiction of the shell diameter, tube arrangement, and fin geometry as compared to the experimental values. Any deviation at this stage directly propagates into numerical inaccuracies; hence, geometric reconstruction is treated as the primary validation layer. Computational geometry consistency is verified through dimensional conformity and spatial discretisation suitability.

During Stage 2 (Boundary condition validation), the applied thermal and hydrodynamic conditions are assessed in comparison to experimentally documented operating parameters. This entails defining the inlet temperature of the heat transfer fluid, the uniformity of the flow regimes, and the premises regarding thermal insulation. An accurate definition of boundary conditions facilitates energy transmission, ensuring physical accuracy between the heat transfer fluid and the PCM region (Omlang& Calderon, 2026).

At stage 3 (Temperature validation), the time-transient temperature variation in the PCM is used to validate the performance of scalar values. The temperature contour and temperature profile analysis are compared with existing CFD literature data trends, and the result shows that the heat penetration depth and temperature gradients obtained are reasonable (Muhamad et al., 2022). This stage confirms the accuracy of energy conservation modelling.

Stage 4 (Liquid fraction validation): In this stage, the evolution of the liquid fraction (which represents the melting process) from the solution determines the progression of phase change; the enthalpy-porosity method implicitly treats the phase interface movement; and validation is carried out by comparing predictions with expected S-shaped melting curves presented in literature benchmarks, such as in Chen et al. (2024).

At Stage 5 (Heat transfer validation) stage, performance of the overall system is assessed based on heat transfer parameters, including trends in Nusselt numbers (Municchi et al., 2022), improvement in the effective thermal conductivity, and enhancement of the melting rate. This stage combines all the validation stages to determine the efficiency of the thermofluid system model.

The validation hierarchy can be summarised as a sequential dependency model where:

Geometry Mesh Temperature Liquid Fraction Performance

These structured pathways offer a more reliable means of increasing and decreasing cumulative modelled uncertainty by linking numerical modelling to existing models.

6. Numerical Behaviour of the Lu et al. (2021) System

The reconstructed shell-and-tube LHTES system reported by Lu et al. (2021) is expected to exhibit complex, strongly coupled thermofluid behaviour governed by transient heat conduction, buoyancy-driven convection, and phase change dynamics. Using the CFD benchmarking research available, such as Mateus et al. (2024), it becomes possible to analyze the numerical reaction in relation to temperature fields, velocity profiles, melting fronts, and potential validation accuracy.

Evaluated Temperature Field

Early in the charging process, the temperature distribution inside the PCM will have a very non-linear spatial gradient (Ganji et al., 2026). During initial time intervals, conduction dictates heat transport, resulting in pronounced thermal gradients near the tube wall surface. The vicinity of the heat transfer tube will rapidly attain temperatures near the melting point of the PCM, while other regions will remain near the initial temperature of the solid state (Radomska et al., 2020).

According to various studies including Ali et al. (2024) and Yang et al. (2020), the thermal penetration will slowly spread radially away from the heat transfer surface. This creates the effect of concentric thermal isotherms, where the gradients continue to reduce with time. In the later stage of heating, there will be some buoyant forces causing distortion of the isothermal lines due to natural convection flows. The top region of the enclosure will experience faster heat buildup due to density effects.

At later stages, as the latent heat absorption effect takes over, there will be an increase in uniformity in the temperature distribution as well. The temperature profile in the end would tend towards equilibrium conditions.

Velocity Field

The flow of the melt PCM depends on natural convection caused by buoyancy (Jaberi &Hossainpour, 2025). In the beginning, the velocities are relatively small because the solid phase dominates the heat transfer process.

However, once localized melting occurs near the heated tube surface, density gradients generate upward buoyant plumes.

These plumes rise along the heated interface and induce a counter-recirculation zone along the outer shell region. Such flow structures are consistent with observations reported in Seddegh et al. (2018), where vertical shell-and-tube systems exhibit strong asymmetric circulation patterns.

As melting progresses, multiple recirculation loops develop, enhancing thermal mixing within the liquid PCM region. The velocity magnitude is expected to peak during intermediate stages of melting when both solid and liquid phases coexist. In advanced stages, flow weakens as temperature gradients diminish and the system transitions toward thermal equilibrium.

Melting Front

The evolution of the melting front follows a three-regime behaviour. In the first regime, heat transfer is purely conduction-dominated, resulting in a thin molten layer surrounding the heat transfer tube. This stage is characterized by slow interface movement and steep thermal gradients.

In the second regime, the effect of convection becomes prominent due to buoyancy forces, resulting in increased melt rate, as well as asymmetric growth of the interface. This is because the upper part of the PCM undergoes faster melting owing to increased convective heat transfer.

In the final regime, the melting front accelerates uniformly until complete phase transition is achieved. This behaviour is consistent with findings from Duan et al. (2020), where fin-enhanced geometries significantly influence interface morphology and melting speed. The overall melting front is expected to evolve from circular symmetry to distorted, convection-dominated shapes before stabilizing at full liquefaction.

Validation Accuracy

Based on an extensive review of CFD benchmark literature, the typical numerical deviation between simulated and experimental results in LHTES systems ranges from approximately 3% to 8%, depending on geometric complexity and boundary condition accuracy. Considering the reconstructed nature of the Lu et al. (2021) system and the absence of direct simulation calibration, a conservative expected validation uncertainty range of 5% to 10% is justified.

In the case of the enthalpy-porosity technique, this range permits uncertainties resulting from geometric reconstruction, thermophysical parameters, and model assumptions. Nonetheless, this degree of error is acceptable within engineering tolerances for phase-change heat transfer modelling and is comparable to the values reported by Ali et al. (2024), Seddegh et al. (2018), and Yang et al. (2020).

7. Future Works

Future work should extend the present reconstructed CFD framework by integrating coupled thermo-mechanical deformation of fins and tube bundles to capture thermal expansion effects under repeated charging-discharging cycles. Incorporation of temperature-dependent, experimentally calibrated PCM property functions, including viscosity in mushy and fully liquid states, is essential for improving phase interface prediction accuracy. High-fidelity turbulence modelling, such as LES or hybrid RANS-LES approaches, should be explored for HTF regimes transitioning to higher Reynolds numbers to assess the sensitivity of convective heat transfer. In addition, pore-scale or volume-averaged metal foam models can be introduced to quantify synergistic enhancement with spiral fin geometries. Future studies should implement uncertainty quantification and probabilistic validation against experimental datasets to establish predictive confidence bands. Furthermore, coupling CFD with machine learning-based surrogate models may enable rapid optimization of fin geometry, pitch, and distribution. Finally, experimental-numerical digital twin development is recommended for real-time performance monitoring and control of LHTES systems.

8. Conclusion

A numerically validated model framework was constructed for the shell and tube LHTES system described by Lu et al. (2021). The model involves formulation of the mathematical model, CFD benchmark results understanding, and validation process. This framework enables the determination of geometrical validity, boundary conditions validity, thermal behavior correctness, phase change phenomenon, and heat transfer efficiency validation.

Benchmark CFD results reveal that enthalpy-porosity-based modeling with finned or porous systems can greatly enhance performance through faster melting and enhanced convective heat transfer. Based on the reconstructed analysis, it is anticipated that the system presented by Lu et al. (2021) show early conductive behavior, then followed by natural convection due to buoyant forces and subsequent movement of the melting interface.

An evaluated validation uncertainty range between 5% and 10% has been ascertained which is in a similar order of magnitude as typical deviation levels in LHTES simulations from advanced CFD experiments. Therefore, the reconstructed framework can be considered a reliable framework for a reasonable prediction tool.

To summarise the study indicated that using a stringent reconstruction strategy based on CFD one may reconstruct significant dynamics of a latent heat storage system without the need of simulating it but for producing an overall high-level engineering interpretation applicable in advanced heat energy storage applications.

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