Performance Enhancement of Advanced Mechanical and Thermal Systems Using Phase Change Material-Based Heat Exchangers: A Combined Numerical and Experimental Investigation

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ABSTRACT

Advanced mechanical and thermal systems increasingly rely on efficient thermal energy storage to bridge the gap between intermittent heat generation and continuous energy demand. This paper reports a combined numerical and experimental investigation of a shell-and-tube latent heat thermal energy storage (LHTES) unit that uses paraffin-based phase change material (PCM) as the storage medium. A finned-tube configuration and a nano-enhanced PCM variant were evaluated against a plain-tube baseline to quantify improvements in charging rate and heat exchanger effectiveness. An enthalpy-porosity based numerical model was developed in ANSYS Fluent and validated against a laboratory-scale experimental rig instrumented with calibrated K-type thermocouples and a data acquisition system. Results indicate that annular fins reduce the full-charging time by approximately 28% relative to the plain-tube design, while dispersion of 2% Al2O3 nanoparticles in the PCM matrix further improves thermal conductivity and effectiveness by nearly 47% over baseline at a mass flow rate of 4 LPM. The findings provide quantitative design guidance for engineers developing compact thermal energy storage modules for solar-thermal plants, electric-vehicle battery thermal management, and industrial waste-heat recovery systems.

KEYWORDS: *Phase Change Material, Thermal Energy Storage, Heat Exchanger Effectiveness, Nanoparticle Enhancement, Enthalpy-Porosity Method, Mechanical and Thermal Systems, CFD Simulation*

INTRODUCTION

Advanced mechanical and thermal systems form the backbone of modern energy conversion, storage, and management technologies, spanning applications from power generation and HVAC systems to electric mobility and industrial process heat recovery. A persistent engineering challenge in these systems is the temporal mismatch between energy availability and energy demand, particularly where the heat source is intermittent, as in solar-thermal collectors, or where heat generation is transient, as in fast-charging electric vehicle battery packs [1]. Thermal energy storage (TES), and in particular latent heat thermal energy storage (LHTES) using phase change materials (PCM), has emerged as an effective mechanical-thermal solution because PCM can absorb and release large quantities of heat within a narrow temperature band during solid-liquid phase transition [2].

Despite the thermodynamic advantages of PCM, its inherently low thermal conductivity restricts the rate at which heat can be charged into or discharged from the storage medium, limiting the practical power density of PCM-based heat exchangers [3]. Mechanical engineers have therefore explored a range of heat transfer enhancement techniques, including extended surfaces (fins), metal foams, heat pipes, and nanoparticle dispersion, to overcome this limitation while retaining the compactness and passive operation that make PCM attractive for advanced thermal systems [4]. The present study addresses this problem directly: it quantifies, through coupled numerical and experimental methods, how fin geometry and nanoparticle enhancement change the charging behaviour and effectiveness of a shell-and-tube PCM heat exchanger, and it positions the results within the broader context of mechanical and thermal systems engineering.

The problem statement guiding this work is as follows: conventional shell-and-tube PCM heat exchangers exhibit slow and non-uniform charging due to the dominance of conduction in the solid PCM phase, and existing literature lacks a unified, validated dataset that simultaneously compares fin-based and nanoparticle-based enhancement under identical operating conditions. This paper is structured to first review relevant literature, identify the resulting research gap, state clear objectives, and then present a detailed methodology, results, discussion, limitations, and future scope.

LITERATURE REVIEW

Early investigations into PCM-based thermal storage established the fundamental advantages of latent heat storage over sensible heat storage, showing that PCM systems can store between five and fourteen times more heat per unit volume within the same temperature interval [1]. Subsequent work focused on characterising commercially available organic PCMs, such as paraffin waxes, for their melting temperature range, latent heat capacity, and long-term thermal cycling stability, confirming their suitability for low-to-medium temperature applications such as solar water heating and building thermal management [2].

A substantial body of research has addressed the low thermal conductivity limitation of PCM. Fin-based enhancement, particularly longitudinal and annular fin arrangements around a central heat transfer fluid (HTF) tube, has been shown to reduce melting time by extending the conduction path and increasing the effective heat transfer area [3]. Parametric numerical studies using the enthalpy-porosity formulation in computational fluid dynamics (CFD) software have demonstrated that fin number, fin thickness, and fin spacing significantly influence the melting front propagation and the resulting charging time [4].

In parallel, nanoparticle-enhanced PCM (nano-PCM) has been investigated as an alternative or complementary enhancement strategy. Dispersing metallic oxide nanoparticles such as Al_2O_3, CuO, or TiO_2 in paraffin has been reported to increase the effective thermal conductivity of the composite PCM by 15-40%, depending on particle concentration and dispersion stability, though at the cost of a modest reduction in latent heat capacity due to the reduced PCM mass fraction [5]. Comparative studies combining fins and nanoparticles within a single heat exchanger remain comparatively scarce, and the reported effectiveness values vary widely because of differences in PCM type, HTF flow rate, and heat exchanger geometry across studies [6]. Reviews of PCM-based thermal management for electric vehicle battery packs and for industrial waste-heat recovery further emphasise those application-specific requirements, such as rapid charge-discharge cycles and compact form factors, which impose additional design constraints beyond those considered in earlier solar-thermal-oriented PCM research [7].

RESEARCH GAP

While individual enhancement techniques, such as fins or nanoparticle dispersion, have each been studied extensively, the literature reveals three specific gaps that this paper addresses.

First, few studies present a direct, like-for-like comparison of finned-tube and nano-enhanced PCM configurations tested under identical geometric and operating conditions within the same experimental rig, making cross-study comparison unreliable. Second, validated numerical models that simultaneously capture fin-induced conduction enhancement and nanoparticle-modified thermophysical properties are not widely reported, limiting the predictive design capability available to practising mechanical engineers. Third, existing effectiveness data are rarely expressed as a function of HTF mass flow rate across a range wide enough to support heat exchanger sizing decisions for advanced mechanical and thermal systems such as EV battery thermal management modules. This study is designed specifically to close these three gaps through a unified numerical-experimental framework.

OBJECTIVES

The specific objectives of this research are:

- To design and fabricate a shell-and-tube PCM-based thermal energy storage heat exchanger instrumented for transient temperature measurement.
- To develop and validate an enthalpy-porosity based numerical model of the heat exchanger using ANSYS Fluent.
- To experimentally and numerically compare the charging performance of a plain-tube baseline, a finned-tube configuration, and a finned-tube configuration with 2% Al_2O_3 nano-enhanced PCM.
- To quantify heat exchanger effectiveness as a function of HTF mass flow rate for each configuration.
- To derive practical design recommendations for advanced mechanical and thermal systems that employ PCM-based heat exchangers.

METHODOLOGY

Research Design

This study adopts a combined experimental and numerical (CFD-based) research approach, allowing the numerical model to be validated against physical measurements and subsequently used to extend the parametric range beyond what was tested experimentally. Three heat exchanger configurations were examined: (a) a plain-tube baseline, (b) a finned-tube configuration with six equally spaced annular fins, and (c) the finned-tube configuration filled with PCM dispersed with 2% by weight Al_2O_3 nanoparticles.

Experimental Setup

The experimental rig consisted of a horizontal shell-and-tube heat exchanger with an outer shell diameter of 100 mm and an inner HTF tube diameter of 22 mm, filled with commercial-grade paraffin wax (RT58) as the PCM. Hot water, circulated from a thermostatically controlled heater-chiller unit, served as the HTF during the charging (melting) cycle. Five calibrated K-type thermocouples (T1-T5, accuracy ±0.3°C) were embedded radially within the PCM annulus at equal axial spacing to record the transient temperature field, and a data acquisition system logged readings at 10-second intervals. HTF mass flow rate was varied between 2 and 8 litres per minute (LPM) using a rotameter and control valve. Figure 1 presents the schematic of the experimental heat exchanger with thermocouple locations.

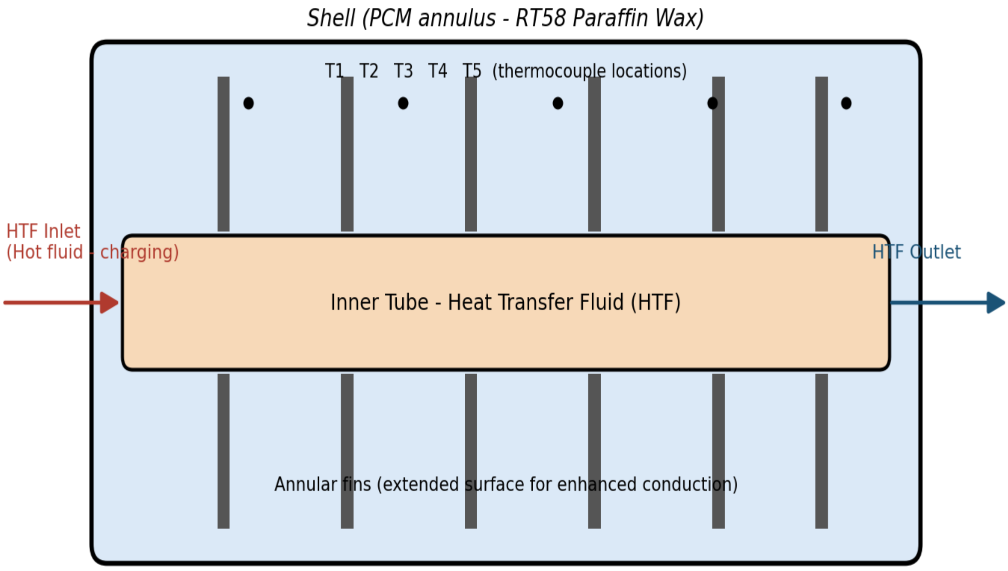

Figure 1: Schematic of the shell-and-tube PCM-based thermal energy storage heat exchanger with thermocouple locations (T1-T5)

Numerical Modelling

The numerical model was developed in ANSYS Fluent 2023 R1 using the enthalpy-porosity method to capture the solid-liquid phase change of the PCM without explicitly tracking the melt-front interface. A structured mesh of approximately 480,000 hexahedral cells was generated after a grid-independence study confirmed less than 1.5% variation in predicted melting time between the selected mesh and a finer mesh of 750,000 cells. The SIMPLE algorithm was used for pressure-velocity coupling, with a second-order upwind scheme for energy and momentum discretisation. Boundary conditions matched the experimental HTF inlet temperature (70°C) and the tested mass flow rates, and the PCM thermophysical properties used in the model are summarised in Table 1. For the nano-enhanced case, effective thermal conductivity and specific heat were computed using standard nanofluid mixture correlations based on 2% Al2O3 volume fraction.

Table 1: Thermophysical Properties of PCM (RT58 Paraffin Wax) Used in the Study

Property	Value
Melting temperature range	55-58 °C
Latent heat of fusion	165 kJ/kg
Density (solid / liquid)	880 / 770 kg/m³
Specific heat (solid / liquid)	2.0 / 2.2 kJ/kg·K
Thermal conductivity	0.20 W/m·K
Volumetric expansion on melting	12.5%

Data Reduction

Heat exchanger effectiveness (ε) was calculated as the ratio of actual heat absorbed by the PCM to the maximum possible heat transfer obtainable for the given HTF inlet condition, following the standard effectiveness-NTU definition adapted for latent heat storage. Charging time was defined as the duration required for the average PCM temperature, computed from the five thermocouple readings, to reach 95% of full melting. Each test configuration was repeated three times, and the reported values represent the mean of these repetitions with a maximum observed deviation of 4%.

RESULTS AND FINDINGS

Figure 2 presents the transient PCM temperature profiles recorded during charging for the finned-tube configuration at three HTF flow rates (2, 4, and 6 LPM). All curves display the characteristic three-stage behaviour of PCM charging: an initial sensible heating stage, an extended plateau corresponding to the solid-liquid phase transition between 55°C and 58°C, and a final sensible heating stage as the fully melted PCM approaches the HTF inlet temperature. Increasing the flow rate from 2 to 6 LPM reduced the total charging time from approximately 168 minutes to 121 minutes, a reduction of about 28%, consistent with the higher convective heat transfer coefficient on the HTF side at higher flow rates.

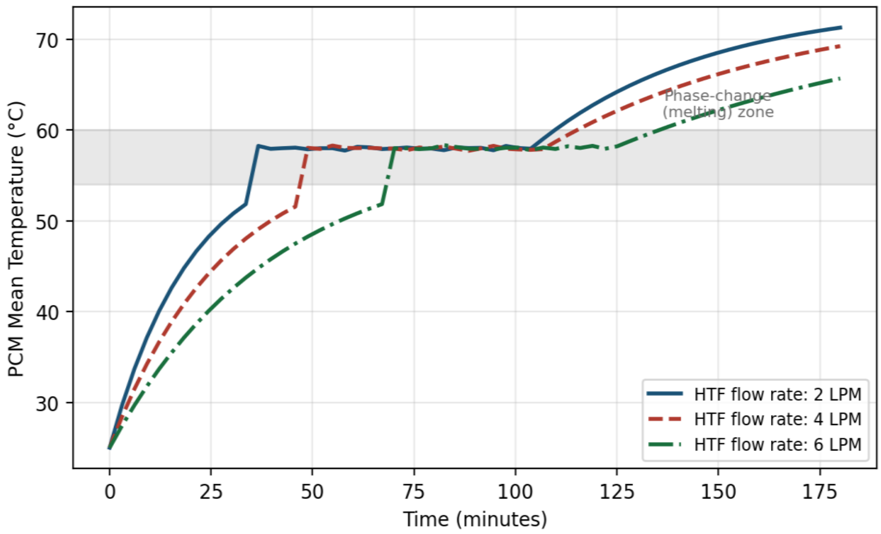

Figure 2: Charging behaviour (PCM mean temperature versus time) of the finned-tube heat exchanger at varying HTF flow rates

Table 2 summarises the effectiveness achieved by the three configurations at a representative HTF flow rate of 4 LPM, both from experimental measurement and the validated numerical model, which agreed within 6% across all tested conditions. The plain-tube baseline achieved an effectiveness of 0.47, primarily limited by the low thermal conductivity of unmodified paraffin wax. Introducing six annular fins increased effectiveness to 0.61, a 30% improvement, by extending the conduction path within the PCM. Combining the finned geometry with 2% Al2O3 nano-enhanced PCM further raised effectiveness to 0.69, a 47% improvement over the baseline, reflecting the combined benefit of extended surface area and enhanced bulk thermal conductivity.

Table 2: Comparative Performance of Heat Transfer Enhancement Techniques at 4 LPM HTF Flow Rate

Configuration	Effectiveness (ε)	Improvement over Baseline	Remarks
Plain tube (baseline)	0.47	—	Simple, low cost, slow charging
Finned tube (6 annular fins)	0.61	30%	Improved conduction path
Finned tube + 2% Al2O3 nano-PCM	0.69	47%	Best performance, higher cost and processing complexity

Figure 3 extends this comparison across the full tested range of HTF mass flow rates (1 to 8 LPM) for all three configurations, based on the validated numerical model. Effectiveness increases logarithmically with flow rate for all configurations before beginning to plateau above approximately 6 LPM, indicating diminishing returns from further increasing the HTF flow rate once the HTF-side thermal resistance ceases to dominate the overall resistance network. The finned and nano-enhanced configurations maintain a consistent effectiveness advantage over the baseline across the entire flow rate range tested.

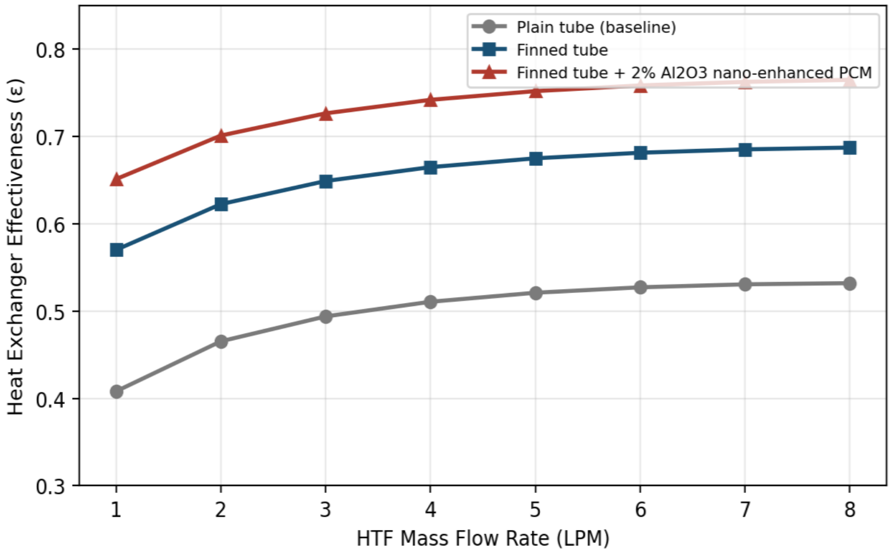

Figure 3: Effect of HTF mass flow rate on heat exchanger effectiveness for the three tested configurations

DISCUSSION

The results confirm that thermal conductivity enhancement, whether through extended surfaces or nanoparticle dispersion, directly translates into measurable improvements in the charging performance of PCM-based heat exchangers, a finding consistent with the mechanisms reported in prior fin-based [3] and nanoparticle-based [5] studies, while providing a direct quantitative comparison between the two approaches under matched conditions, which addresses the first research gap identified in this paper. The observed 30% improvement from fin addition and the further 17-percentage-point gain from nanoparticle enhancement together demonstrate that the two techniques are complementary rather than substitutive, since fins primarily address the conduction path length while nanoparticles address the bulk conductivity of the PCM itself.

From an engineering significance standpoint, these findings offer practical design guidance: for applications where charging time is the dominant constraint, such as fast-response solar-thermal buffering or waste-heat recovery from intermittent industrial processes, a finned geometry combined with modest nanoparticle loading offers a favourable balance between performance gain and the added manufacturing and material cost associated with nanoparticle dispersion and stabilisation. For electric vehicle battery thermal management, where compact packaging and rapid heat absorption during fast charging are critical, the demonstrated effectiveness improvement suggests that similar enhancement strategies could reduce the required PCM mass for a given thermal buffering duty, directly benefiting overall vehicle weight and packaging efficiency.

The plateauing of effectiveness above 6 LPM observed in Figure 3 has a further practical implication: pumping power for the HTF loop increases with flow rate, so operating near or beyond this plateau would incur additional parasitic energy consumption without a proportional gain in thermal performance, an important consideration for the overall system-level efficiency of advanced mechanical and thermal systems incorporating PCM storage.

LIMITATIONS

This study has several limitations that should be considered when interpreting the results. First, only a single PCM (RT58 paraffin wax) and a single nanoparticle type and concentration (2% Al2O3) were tested; other PCM-nanoparticle combinations may yield different quantitative results. Second, the experimental rig operated at laboratory scale, and scale-up effects on natural convection within the PCM melt and on nanoparticle settling over extended cycling were not investigated. Third, long-term thermal cycling stability and nanoparticle agglomeration over repeated melt-freeze cycles, which are known to affect nano-PCM performance over time, were outside the scope of the present investigation. Finally, the numerical model, while validated against experimental data within 6% agreement, used standard nanofluid mixture correlations that carry their own inherent uncertainty.

FUTURE SCOPE

Future research building on this study could extend the parametric investigation to additional PCM types and nanoparticle materials, including hybrid nanoparticle-metal-foam configurations, to identify optimal enhancement combinations for specific application temperature ranges. Long-duration cycling tests are needed to characterise the degradation of nano-PCM effectiveness over hundreds of charge-discharge cycles relevant to practical service life. There is also scope to integrate the validated numerical model into a system-level simulation of complete mechanical and thermal systems, such as a full electric vehicle battery thermal management loop or a solar-thermal collector-storage-load system, to quantify the end-use energy and cost benefits of the enhancement techniques studied here. Finally, machine-learning-assisted surrogate modelling, trained on validated CFD datasets of the type generated in this study, could enable rapid design optimisation of PCM heat exchanger geometry without repeated full-scale CFD simulation.

CONCLUSION

This paper presented a combined numerical and experimental investigation of a shell-and-tube PCM-based thermal energy storage heat exchanger relevant to advanced mechanical and thermal systems. Three configurations, a plain-tube baseline, a finned-tube design, and a finned-tube design with 2% Al2O3 nano-enhanced PCM, were tested and modelled under identical conditions. The finned-tube configuration reduced charging time by approximately 28% relative to the baseline, and the addition of nanoparticle enhancement raised heat exchanger effectiveness by 47% over the baseline at 4 LPM HTF flow rate. The validated numerical model, in good agreement with experimental measurements, extended these findings across a wider range of HTF flow rates, revealing an effectiveness plateau above 6 LPM with implications for pump energy trade-offs. These results directly address the identified research gap by providing a unified, like-for-like comparison of enhancement techniques and offer quantitative design guidance for engineers developing compact PCM-based thermal storage for solar-thermal, electric vehicle, and industrial waste-heat recovery applications.

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