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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF PHASE-CHANGE MATERIAL-INTEGRATED HEAT EXCHANGERS FOR THERMAL ENERGY STORAGE: A CRITICAL REVIEW

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ABSTRACT

This critical review examines experimental and computational investigations of phase-change material (PCM)-integrated heat exchangers for latent thermal energy storage. It compares shell-and-tube, finned-tube, plate and encapsulated arrangements, with attention to transient melting and solidification, heat-transfer enhancement, charging power, cycling, numerical validation and reproducibility. The literature indicates that fins and conduction pathways can accelerate charging but may reduce active PCM volume or raise cost. The review outlines a paired experimental–numerical protocol and recommends reporting stored energy, power, melting fraction and uncertainty together.

KEYWORDS: Phase Change Material; Latent Thermal Storage; Finned Heat Exchanger; Enthalpy–Porosity; Solidification; Numerical Validation.

1. INTRODUCTION

Latent thermal energy storage helps reconcile a mismatch between supply and demand by storing heat around the melting temperature of a phase-change material. Unlike a simple hot-water tank, a PCM vessel can hold a useful quantity of energy within a comparatively narrow temperature interval. The advantage is conditional: a PCM that melts at the wrong temperature or transfers heat slowly may provide less useful power than an appropriately sized sensible store.

When embedded within a heat exchanger, the PCM interacts with the heat-transfer fluid through tubes, plates, fins or encapsulation walls. Fluid-side heat-transfer coefficients, wall

conduction and transient phase-front motion all matter. Natural convection may substantially affect melting while solidification is frequently more conduction-limited. As a result, discharge performance cannot be inferred from charging measurements alone.

2. Historical Development and Importance

The progression from basic latent storage to enhanced PCM exchangers has been driven by applications requiring compactness and peak-load shifting. Early thermophysical-property screening expanded into finned and multitube concepts, followed by enthalpy-based CFD and combined experimental–numerical validation. More recent work tests combinations of fins, porous matrices, encapsulation and machine-learning surrogates, but uneven testing protocols still complicate fair comparisons.

Engineering importance is assessed against a realistic reference configuration: energy delivered at useful temperature, auxiliary work, capital and maintenance requirements, reliability, and operational constraints. This avoids labeling a design superior solely because of one locally favorable heat-transfer number.

3. Review Methodology

A structured critical-narrative review was prepared using publisher and scholarly publication records accessible online. Search terms combined the specific technology with experimental, numerical, modeling, optimization, performance, and review. Directly relevant experimental and numerical articles were prioritized; adjacent established literature and textbooks were used for fundamental equations and interpretation. The reference list identifies the sources used as technical context and supporting literature; this is not claimed as an exhaustive PRISMA systematic review.

Evidence was compared by physical configuration, operating boundary conditions, measurement or calculation method, validation level, useful performance metrics, and principal limitations. Where papers use different conditions or incompatible measures, no pooled improvement percentage was computed. Proposed experiments and calculations below are future methodology, not completed work.

4. Literature Survey and Critical Synthesis

Recent comprehensive reviews of PCM thermal systems [1, 2] organize the field around melting–solidification physics and heat transfer augmentation. They note that larger surface area is not an unconditional benefit because extra fins displace storage material and can

impose fabrication penalties. Their most useful contribution for experimental design is to separate energy capacity from instantaneous charging rate.

Saleh and Mussa [3] compared configurations of longitudinal fins by numerical simulation and experimental investigation. The comparison illustrates that fin position and dimensions affect the spatial melting process, not simply total fin area. The reported advantage of a modified configuration is geometry- and boundary-condition-specific, and should not be converted into a general percentage gain for other PCMs or tube layouts.

Tamraparni and co-workers [4] demonstrated a finned-tube heat-exchanger approach intended to serve several hours of building thermal demand. The importance is system-level: charging and discharging duration must align with a real load-shifting window. A design judged only by reduced melting time can still fail if its discharge temperature is inadequate.

Ali and co-workers [5] synthesized integrated solar collector–PCM storage arrangements, drawing attention to collector temperature, PCM selection and heat-transfer-fluid compatibility. Their findings reinforce the need to select the melting interval from the intended operating schedule rather than choose a material because it has high latent heat on a data sheet.

Recent surveys of solar thermal storage and cascaded PCMs [7, 8] discuss staged melting temperatures as a route to reducing irreversibility. However, the capital cost, hydraulic complexity and partial-charge behavior can offset the theoretical advantage. The relevant comparison is useful energy per unit installed cost, not nominal latent heat alone.

The growing use of hybrid physics and machine learning methods [3, 9] offers rapid screening of geometry, flow and PCM properties. Yet a surrogate trained on a narrow simulation dataset is not a substitute for uncertainty analysis, grid independence or physical validation. It should be regarded as a design accelerator bounded by its training domain.

5. Recommended Experimental and Numerical Methodology

(1) Identify the intended thermal duty, supply/return temperatures, required operating hours and allowable volume before selecting PCM candidates. Screen melting interval, latent heat, conductivity, density, supercooling, segregation and cycling stability.

(2) Create matched exchanger variants: an unfinned reference, a longitudinal-finned design, a radial-finned design and a compact plate configuration. Keep overall envelope volume, metal mass or PCM volume explicit, since each comparison answers a different engineering question.

(3) Apply a transient energy equation with temperature-dependent enthalpy, conduction through solids and an enthalpy–porosity treatment for liquid-zone motion where justified. Perform grid and time-step studies and track total heat balance.

(4) Measure inlet/outlet temperatures, mass flow, wall and bulk PCM temperatures and charging/discharging times. Compare simulations against multiple independent sensor locations, not only one outlet-temperature trace.

(5) Use capacity, charge/discharge power, effectiveness, thermal response time, energy density, exergy efficiency, pressure loss and cycle degradation as concurrent performance indicators.

6. Discussion and Comparative Analysis

Table 1 contrasts representative design or modeling choices. The comparisons are qualitative because reported absolute performance depends on fluid, geometry, loading, boundary conditions and evaluation method.

Enhancement strategy	Potential advantage	Main technical limitation
Extended fins	Shorter melting duration	Lower PCM inventory; fin cost
Metal foam or graphite	Higher effective conductivity	Porosity and contact resistance
Multiple PCMs	Better temperature matching	More complex charge control
Plate geometry	High area density	Leakage and cleaning constraints
Encapsulated PCM	Modular replacement	Added capsule wall resistance

Table 2 sets out common reporting criteria needed to prevent misleading cross-study comparisons. In particular, improvements should be assessed against a clearly stated reference case, with energy conservation and auxiliary inputs included.

Comparison dimension	Recommended reporting practice	Reason
Reference baseline	Same envelope, duty and operating boundary conditions	Controls confounding
Thermal benefit	Heat duty, outlet temperatures, useful efficiency or COP	Captures service value
Hydraulic/electric cost	Pressure drop, pumps/fans/compressor electricity	Captures parasitic energy
Validation	Separate experiments, numerical grid/time checks	Tests reliability
Economic/reliability	Cost, material compatibility, long-term cycling	Tests deployability

Across the surveyed literature, a persistent issue is that attractive performance often arises under favorable flow conditions or a narrow set of thermal loads. Comparisons that omit boundary differences, capital cost or auxiliary consumption are incomplete. It is therefore

preferable to present normalized and absolute results side by side, discuss measurement error, and expose multi-objective trade-offs rather than identify a single universally optimal configuration.

7. Research Outcomes and Gaps

The defensible outcome of this literature synthesis is a measurement framework, not a fabricated performance improvement. High-performing PCM exchangers combine appropriate transition temperature, low internal conduction resistance, usable storage inventory and adequate fluid-side exchange. The main research gap is consistent testing under matched boundary conditions, especially for repeated cycling and realistic part-load operation.

Suggested next steps are paired-design validation, systematic sensitivity studies, transparent uncertainty propagation and independent replication under part-load or off-design conditions. The review identifies research opportunities; it does not certify that any proposed study is wholly novel.

7.1 Material selection and phase-transition range

PCM screening starts with the useful heat-transfer-fluid supply and return temperatures rather than a catalogue ranking of latent heats. An organic paraffin may offer chemically stable cycling and modest subcooling, whereas salt hydrates can provide higher volumetric capacity but may exhibit segregation or supercooling. A defensible study should measure melting and freezing over repeated cycles by differential scanning calorimetry and verify whether the transition interval remains inside the process operating range. Effective conductivity, density, latent enthalpy and the fraction of material that actually completes its transition must be combined when estimating storage performance. Heat capacity outside the phase-change region also contributes to the stored energy and cannot be ignored.

7.2 Energy conservation and enthalpy formulation

The governing thermal model balances transient storage against conductive and convective exchange. In an enthalpy formulation the local total enthalpy is sensible enthalpy plus liquid fraction multiplied by latent heat, with the liquid fraction varying across a finite phase-change interval. The conduction term uses local thermal conductivity; any velocity field in the molten region introduces an advective term. This representation avoids prescribing a sharp moving interface and can be solved on a fixed mesh. The enthalpy–porosity method often damps momentum in the solid region with a mushy-zone source. The numerical constant in

this source is influential, so its sensitivity should be documented rather than concealed as a software default.

7.3 Why charging and discharging differ

During melting, buoyancy can generate liquid circulation once enough of the PCM has liquefied; the influence depends on orientation, viscosity, enclosure size and temperature gradients. During freezing, the solid layer grows near the heat-transfer surface and may suppress natural convection. Consequently, the best fin position for fast melting may not be best for uniform solidification. A paper describing only charging transients leaves the usefulness of the store unresolved. Measurements should include at least one fully completed discharge under a known inlet-fluid temperature and mass flow. For a multi-day application, the fraction of charge recovered each cycle is an important practical output.

7.4 Geometry and comparison basis

A longitudinal-finned tube and a plain tube can be compared at equal envelope volume, equal mass of metal or equal PCM inventory, but the resulting rankings need not agree. At equal volume, additional fins reduce storage capacity; at equal PCM inventory, a finned design may require a larger enclosure. Plate exchangers can offer a more uniform phase-front distance but carry sealing and thermal-contact challenges. The study should therefore define at least two comparisons: a capacity-normalized result and a system-volume-normalized result. This makes the trade-off between charging power and stored energy transparent, and avoids describing the fastest melting configuration as universally best.

7.5 Measurement plan and uncertainty

A credible test rig records heat-transfer-fluid temperatures at calibrated inlet and outlet locations and measures flow with an uncertainty appropriate to the expected small temperature rise. PCM temperatures should be sampled at several radial and axial locations, since one thermocouple cannot describe the moving phase front. The water-side heat rate can be approximated by mass flow multiplied by heat capacity and the measured temperature difference. Heat losses through the vessel wall should be characterized using insulation tests or a separate heat-loss model. Repeated runs are required to distinguish operating variability from instrument bias. Propagated uncertainty in temperature difference becomes especially significant when the fluid temperature change is small.

7.6 Numerical validation hierarchy

Validation should proceed from material properties to transport physics and finally complete exchanger behavior. First, use measured melting intervals and conductivity in a simple calibration case. Second, check energy conservation, grid independence and time-step

independence for the enclosure model. Third, compare transient fluid outlet temperature and multiple PCM-temperature trajectories against the experiment. Only after these steps should a parametric study vary fin pitch or tube number. A simulation matching overall stored energy but missing local melting dynamics may produce unreliable predictions for altered geometries. This distinction matters when using CFD as the source of training data for reduced-order or machine-learning models.

7.7 Power density versus energy density

Storage energy density indicates how much energy fits into the material or device volume; power density indicates how rapidly that energy can be accepted or delivered. Increasing fin content often raises power density while decreasing the volume available for latent storage. A useful compact-storage objective may be recoverable energy above a specified temperature within a fixed discharge interval. Reporting only the duration of complete melting can be misleading if the fluid outlet becomes too cold to serve the load before the PCM fully solidifies. Normalized quantities should retain the associated absolute capacity, material mass and imposed heat-transfer-fluid conditions.

7.8 Cycling durability and system integration

PCM performance can deteriorate through phase separation, leakage, corrosion, encapsulation failure, or changes in thermal contact. Repeated thermal cycles, including partial cycles, are therefore a necessary bridge between proof-of-concept experiments and practical storage duty. If the exchanger is coupled with solar collectors or a heat pump, its operating temperature may change daily and the PCM may not fully melt. A long-duration test should track change in transition temperature, energy recovered per cycle and pressure loss. Designers should also report containment compatibility and maintenance access; a high-conductivity composite is not automatically preferable if it has poor structural or chemical stability.

7.9 Exergy and thermal matching

The first-law energy stored in a PCM can be large even when the temperature of recovery is too low for the intended service. Exergy analysis accounts for heat quality relative to ambient conditions, exposing losses due to excessive temperature differences during charging and discharging. Cascaded PCMs with different melting intervals may reduce temperature mismatch but introduce additional interfaces, valves and control requirements. Comparing exergy efficiency alongside energy efficiency can therefore change the preferred configuration. For domestic hot water, process heat or HVAC applications, the delivered

outlet temperature profile should be matched against the actual temperature requirement rather than a generic nominal operating point.

7.10 Optimization and research perspective

A useful optimization varies fin geometry, number of tubes, PCM grade, flow rate and enclosure volume simultaneously under constraints on cost and mass. Response surfaces or machine-learning surrogates can accelerate this exercise, but their training data must represent the relevant phase-change regimes and be checked with independent simulations. A Pareto front may trade charging time against stored energy density and capital cost. The next experimental contribution should be a matched comparison of at least two enhancement strategies during repeated realistic cycles with uncertainty bars, not merely a new geometry tested once under a convenient constant inlet temperature.

7.11 Thermal capacity and energy bookkeeping

For a PCM module the total stored energy comprises sensible heating of the solid before melting, latent heat consumed as the liquid fraction rises and sensible heating of the liquid afterward. The ideal latent contribution equals the PCM mass multiplied by the specific latent heat; however, this upper bound should not be labeled recovered energy. The experimentally recovered energy is the time integral of fluid mass flow multiplied by fluid heat capacity and outlet-minus-inlet temperature during discharge, after accounting for the test-loop energy balance. The integration should stop at the minimum useful outlet temperature, not necessarily at complete solidification. Reporting both theoretical capacity and usable recovered energy is necessary.

7.12 Dimensionless evaluation

Fourier number compares thermal diffusion time to the characteristic conduction time, while Stefan number compares sensible temperature driving energy with latent heat. Natural convection may be characterized through Rayleigh number when liquid flow and enclosure orientation justify that description. These nondimensional groups help explain why a model validated for one vessel size may not transfer to another. In a typical parametric program the inlet-temperature driving difference, characteristic length and PCM thermal properties should be systematically varied. If only mass flow is swept while all geometry and temperature scales remain fixed, the resulting trends are insufficient to demonstrate general design rules.

7.13 Economic and practical acceptance criteria

Industrial adoption depends on repeated-cycle performance, unit procurement cost, embodied impacts of fins and encapsulation, and the cost of pumps and controls. A high-conductivity additive may increase discharge power but also raise procurement cost, compromise stability

or lower latent storage mass per unit device volume. The appropriate comparison is delivered heat per currency unit or equivalent annual service at the required temperature. A prototype intended for peak cooling should also be assessed for cycling between daily minimum and maximum ambient temperature. This practical lens can reverse laboratory rankings based solely on idealized melting time.

8. CONCLUSION

PCM integration is most useful when thermal storage temperature, discharge power and duty schedule are designed together. Experiments and CFD should be used as complementary tests of the same control volume. Future studies should compare enhanced geometries using both energy-density and power-density metrics and disclose long-duration reliability.

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