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A Review Study on the Use of Phase Change Materials in Heat Exchangers: An Overview of Hybrid Techniques for Thermal Performance Enhancement

Noor Abdulmutalb, Hiba Hameed Kareem

Mustansiriyah University, Department of construction and project management, Baghdad, Iraq.

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ABSTRACT

In this review paper, phase change materials (PCM) usage in the heat exchangers are explored with attention paid to hybrid enhancement methods to enhance the thermal performance and energy stores. PCMs have been well known to have a high latent heat capacitance as well as a capability to hold and release thermal energy at approximately steady temperatures, which qualifies them as application in solar thermal systems, energy management in buildings, waste heat recovery, and thermal management in industries. Nonetheless, their widespread application in heat exchangers is hampered by a thermal conductivity, which is similarly low preventing thermal conductivity, lowering the speed of melting and solidification and reducing the total efficiency of heat conduction. In order to overcome this shortcoming, the recent past has seen studies on various improvement measures such as the use of extended surfaces and novel fin geometries, nanoparticles-enhanced PCMs, metal foams and device optimum shell-and-tube designs. Hybrid methods involving fins and nano-enhanced PCMs have proved to have high synergistic gains of melting, uniformity of temperatures, and efficacy of the system. Computational fluid dynamics (CFD) models have also been used to predict thermal behavior, optimization of geometry and validate experimental results. In spite of the significant advancement, issues including long-term stability, supercooling, material compatibility, manufacturing complexity and cost are still obstructions to large-scale adoption. Overall, there is high potential of the use of hybrid PCM-based heat exchanger as a next generation thermal energy storage system, especially in the renewable energy system, as long as material durability, standardization and economic viability are refined.

1. INTRODUCTION

The world energy environment is experiencing a radical change to more renewable and sustainable energy structures with the stigma to curb climate change and reliance on the fossil fuels. The most essential directions on the way to achieving these goals are solar thermal energy, industrial waste heat recovery, and innovative systems of thermal management. The infrequent feedback of the renewable energy sources and the inability of these sources to meet the energy requirements with the demand at a certain moment in time, however, contribute to the necessity of efficient, reliable, and the high density of thermal energy storage (TES) solutions [1]. Latent Heat Thermal Energy Storage (LHTES) systems that take advantage of Phase Change Materials (PCMs) have been studied extensively and received

Corresponding author E-mail address: noor.abdmutalib@uomustansiriyah.edu.iq

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considerable attention in terms of exceptional capability to store and release thermal energy in large amounts and nearly constant temperatures as they undergo solid-liquid phase change [2].

PCMs present a range of benefits over sensible heating storage systems such as much larger densities of energy storage (generally 5-14 times higher in unit volume), less storage volume, and almost isothermal performance during discharge and charge cycles [3]. All these properties render PCMs very universal in the use of solar thermal power plants, energy management of buildings, electronic cooling applications, cold chain logistics and industrial waste heat recovery applications [4]. Heat exchanger is a critical interface in LHTES systems, or it is a component that is associated with the exchange of thermal energy between PCM and the Heat Transfer Fluid (HTF) in the course of both charging and discharging processes.

Although these strong points suggest that PCM-based heat exchangers are the future technology in HSCs, a basic materials issue problem has been the existence of a serious limitation on cell operation that is based on the nature of many organic and inorganic PCMs: most organic and inorganic PCMs possess low thermal conductivity, usually between 0.1 and 0.6 W/m·K [5]. This thermal resistance forms large temperature gradient in the PCM region, which slows down melting and solidification rates, partial transition of phases in remote parts as well as decreased overall effectiveness of the system. Melted PCM will accumulate around heat transfer surfaces during the charging process forming insulating layers which become increasingly larger impediments to heat transfer to solid PCM core. On the other hand, upon the discharging process, solid PCM develops next to cold surfaces, which also hinders the removal of heat by the liquid PCM [6].

The purpose of this general overview is to come up with a systematic review of the current state-of-the-art in PCM-enabled heat exchanger with specific reference made to the techniques of hybrid thermal enhancement.

2. CLASSIFICATION AND THERMOPHYSICAL PROPERTIES OF PCMS

Materials that are used as phase change materials in storing thermal energy are essentially divided into three major groupings, namely organic, inorganic salts, and eutectic mixtures. The categories have different thermophysical properties, benefits and disadvantages that determine the types they are applicable in certain applications of heat exchanger.

Organic PCM such as paraffin waxes, fatty acids and polyethylene glycosides (PEG) is the best studied category because of its desirable properties such as chemical stability, non-corrosiveness, congruent melting behavior and low supercooling tendencies [7]. The petroleum refining processes produce paraffin waxes with melting temperatures of 40 ^{o}C to 80 ^{o}C, and the latent heat of 150-250 kJ/kg. They are however, incredibly low in thermal conductivity (around 0.2 W/m·K) and even bear a flammability issue that needs proper containment measures. Lauric acid, palmitic acid and stearic acid are fatty acids, which are richer in thermal conductivities (0.3-0.4 W/m·K) and could be sourced more readily, but are associated with high costs and olfaction problems [8].

Organic PCMs Ge and popular materials are salt hydrates (e.g. $CaCl_2 \cdot 6H_2O$, $Na_2SO_4 \cdot 10H_2O$, $MgCl_2 \cdot 6H_2O$) with much higher latent heat capacities (150-300 kJ/kg) and thermal conductivities (0.5-1.0 W/m·K) than organic materials [9]. They are affordable and nonflammable which makes them appealing towards the mass implementation. Nevertheless, salt hydrates come with major issues such as phase separation, supercooling, and corrosion tendencies against metallic containment materials meaning that one requires to pay close attention to the compatibility evaluation of the material and the inclusion of a nucleating agent.

Eutectic mixtures, which are a combination of two or more organic or inorganic, allow the careful setting of the phase transition temperatures to suit the particular application needs and congruent melting characteristics [10]. Such manufactured materials reduce the problem of phase segregation, which is common in salt hydrates, and may realize intermediate thermal capabilities between the constituent materials.

Table 1 presents a classification and properties of common phase change material and figure 1 presents thermophysical property comparison in PCMs.

Table 1: Classification and Properties of Common Phase Change Materials.

Category	**Material**	**Melting Temp. (°C)**	**Latent Heat (kJ/kg)**	**Thermal Conductivity (W/m·K)**	**Advantages**	**Limitations**
Organic	Paraffin wax	40–80	150–250	0.2	Chemically stable, non-corrosive	Low conductivity, flammable
Organic	Fatty acids	45–70	180–220	0.3–0.4	Renewable source, higher conductivity	Higher cost, odor
Inorganic	$CaCl_2 \cdot 6H_2O$	29	190	1.0	High conductivity, low cost	Phase segregation, corrosive
Inorganic	$Na_2SO_4 \cdot 10H_2O$	32	254	0.5	High latent heat, inexpensive	Supercooling, incongruent melting
Eutectic	Capric-Lauric acid	21	143	0.2	Tailored melting point, stable	Lower latent heat
Eutectic	$MgCl_2 \cdot 6H_2O$-$Mg(NO_3)_2 \cdot 6H_2O$	59	132	0.6	Moderate temperature, stable	Complex preparation

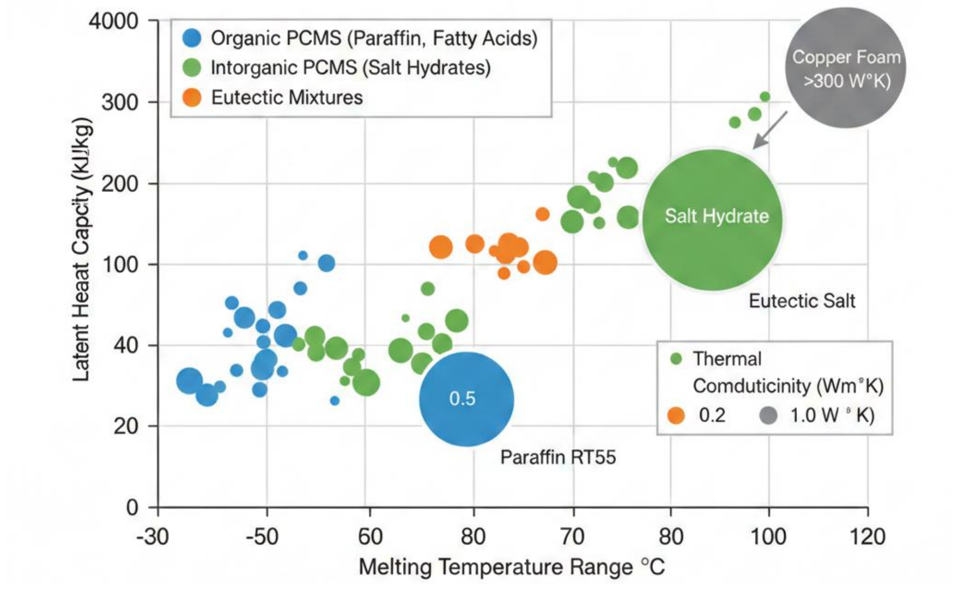

Figure 1: Comparison chart of thermophysical properties at different temperatures of latent heat capacity against ranges of melting temperatures of different categories of PCM with bubble size relevant to thermal conductivity.

3. EXTENDED SURFACES AND FIN CONFIGURATIONS

The use of long surfaces that are often known as fins is one of the most established and the most used ways in which the heat transfer in PCM-based systems can be improved. PCM fins made of highly thermally conductive substances (usually aluminum, copper or graphite) enhance the apparent amount of heat transfer between PCM domain and expression of the HTF containment surface, in effect lessening the conduction route length inside the low-conductivity PCM [11].

3.1 Geometric Configurations and Performance

Recent studies have investigated a wide range of other, non-traditional fin geometries other than longitudinal or annular. Longitudinal fins on tube walls are simple to manufacture, and offer moderate performance enhances, with a shorter melting time by 30-50 percent, usually, depending upon the fin thickness, length and spacing [12]. Nevertheless, identical longitudinal fins can tend to form stagnant areas between the fin surfaces on which natural convection is inhibited, and which lead to poor general performance.

In radial designs, higher amounts of surface area are provided by annular and circumferential colored fins around the tubes, to enhance uniformity in heat dispersion around the circumference of the tube. Experiments show that annular fins may increase the melting rates (40-60 percent higher than with bare tubes), where the optimal PCM costs are based on the tradeoff between a larger surface area and a smaller PCM volume [13].

3.2 Innovative Fin Geometries

Recent innovations have brought biomimetic and constructal-inspired designs of fins that optimize heat transfer with non-uniform designs. The tree-shaped fins that were inspired by the branching structures found in nature have shown great performance through gradual distribution of surfaces area in the transfer of heat all over the PCM domain [14]. Experiment studies, based on numerical methods, indicate that fin configurations that are optimized as trees can still reduce the complete melt duration by 67 percent relative to the enclosures without fins, whereas the rectangular fins decrease by 41 percent and constructal fins reduce by 53 percent. The bifurcated configuration allows penetration of heat to distant areas of PCM besides having routes of natural convection flow.

Bifurcated fins with Y-branching designs have been seen to be especially effective in annular tube designs, where they enhance the mixing process and the evenness of temperature distributions that are otherwise in straight fins designs [15]. According to experimental and numerical research, bifurcated fins could be very effective in enhancing thermal performance within latent heat storage heat exchangers in terms of breaking the development of thermal boundary layers and encouraging secondary flow channels.

In the shape of swirl, helical and helical fins to add convective heat transfer during melting. Farahani et al. revealed that continuous spiral fins enhanced 31.8 percent of melting rates compared with unfinned design whilst rectangular continuous fins raised 37.87 percent of rates enhanced [16]. The three dimensional structure of spiral structures also encourages movement of the fluid in more directions thereby dehumidifying thermal stratification.

Natural convection has been explored using sinusoidal and wavy fins in order to be geometrically perturbed. Tavakoli et al. tested the performance of sinusoidal internal fins in thermo-hydraulic, and proved stronger and better heat transfer coefficients by disruption of the flows with low pressure drop properties [17].

Table 2 demonstrates the comparison of the performance of different fin geometries and figure 2 demonstrates the dampen up of the scheme and contours of the melting fronts of the advanced fin.

Table 2: Performance Comparison of Various Fin Geometries.

Fin Type	Melting Time Reduction	Manufacturing Complexity	PCM Volume Reduction	Cost Impact	Natural Convection Enhancement
Longitudinal	30–50%	Low	15–25%	Low	Moderate
Annular	40–60%	Medium	20–30%	Low	Moderate
Tree-shaped	67%	High	25–35%	Medium	High
Bifurcated	55–65%	High	20–30%	Medium	High
Spiral	32–38%	Medium	15–20%	Low	High
Sinusoidal	25–35%	Medium	10–15%	Low	Moderate

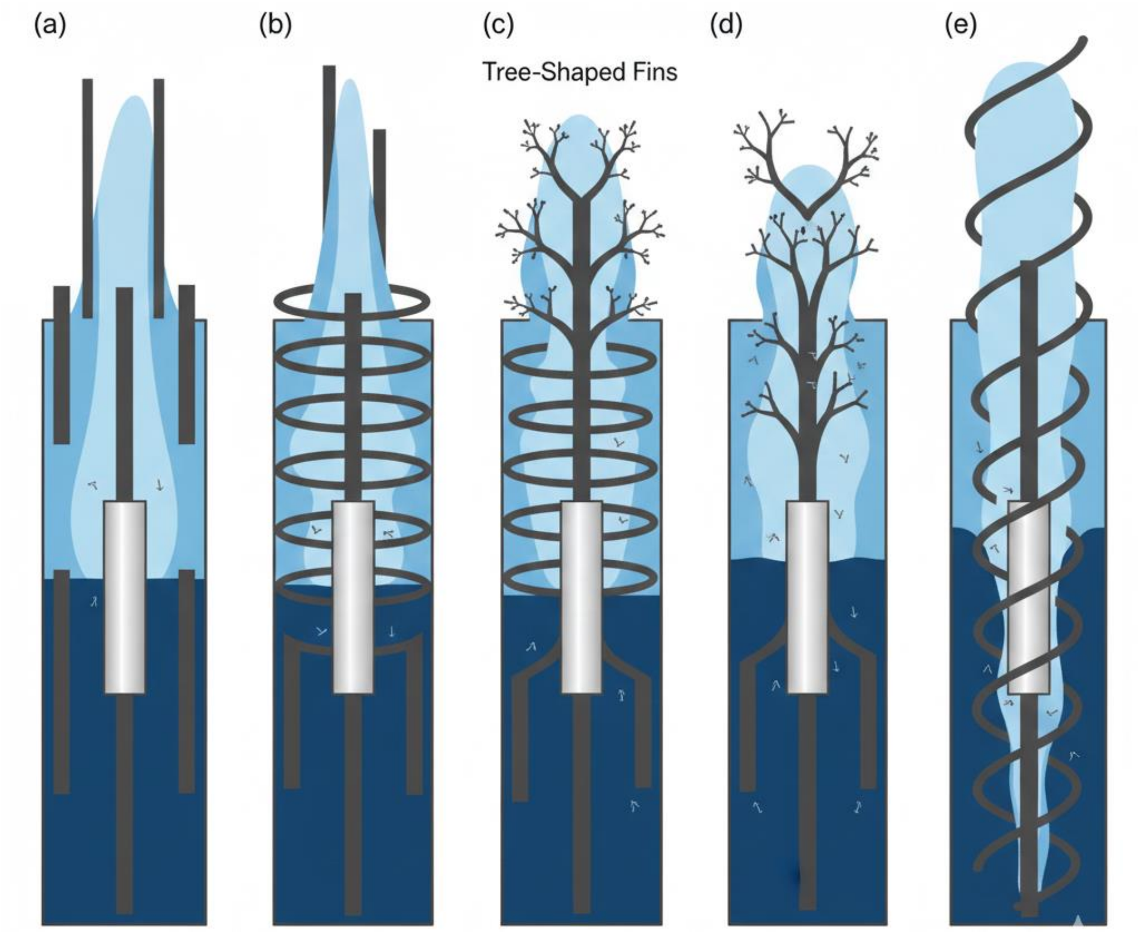

Figure 2: Longitudinal, annular, tree, bifurcated and spiral fins schematics on geometric basis illustrating case of (a) longitudinal fins, (b) annular fins, (c) tree like fins, (d) bifurcated fins and (e) spiral fins and associated contours of melting front at 50 percent completion.

3.3 Design Optimization Considerations

Fin design optimization involves tradeoffs or optimization amongst competing purposes. Thickening fin and increasing fin length makes more area available to heat transfer, but less PCM volume will be available to store all the heat energy. The best spacing between the fins should allow the natural convection currents and give the maximum amount of surface area density of the fin. Choice of the material is subject to tradeoffs between thermal conductivity (copper: ~400 W/m·K, aluminum: ~237 W/m·K)), density, cost, and compatibility with PCMs (corrosion) [18].

Some more recent research has used genetic algorithms and neural networks to show that optimal fin setups can perform better than geometrical designs which are manually designed based on intuition. Bie et al. made dimensionless normalized indexes of finned multi-tube system and have found that the fin diameter effect is more dominant than the effect of fin number or tube diameter on the general heat transfer rate [19]. Their optimization would provide configurations that attained 25 percent shorter complete melting time, 3-hour increase in volume of heat storage, although varying between discharging processes.

4. NANOPARTICLE-FIN HYBRID SYSTEMS

This hybrid method of making PCMs nanoparticle-enhanced and with increased surface area is some logical combination where nanoparticles are aimed to improve volumetric conductivity and increased surface area (fins). This hybrid approach can overcome the shortcomings of each strategy: individual techniques cannot be used to enhance conductivity in the distant PCM areas due to the use of fins, and nanoparticles cannot be used to enhance the surface area due to limited surface area.

4.1 Synergistic Effects

Nobrega et al. examined the joint effect of fins and nano-PCM mixtures under tubular structures [20]. Their results showed that the reduction in solidification time was as high as 9.1 under the influence of the use of fins whereas the increase of nanoparticle concentration enhances solidification without references to the presence of fins. Combination of the two displayed additive advantages with optimal concentrations of nanoparticles (1-3 wt%) failing to impose viscosity penalties evidently lowering natural convection between the fins.

Addiction of Cu-water nanofluid into PCMs in finned heat sink has reported reduction in temperatures by 6.41 percent and Nusselt number by 4.6 percent relative to pure PCM configurations [21]. The heat sinks of square fin shape performed better (13.41% decrease in temperature) than the circular and triangular shaped sink with the combination of nano-enhanced PCMs.

4.2 Optimization Considerations

The competing effects should be critically optimized with hybrid nanoparticle-fin systems. Super-nanoparticles induce viscosity and may inhibit natural convection that fins are set to achieve. The spacing of the fins should also be able to handle the changed flow properties of NePCMs that have dissimilar Prandtl numbers and Rayleigh numbers to base PCMs. Recent research indicates that lower levels (0.5-2 wt%) of nanoparticles can be utilized with finned systems in which convection has a pronounced contribution whereas higher levels (3-5 wt%) can be applied with conduction-based systems [22].

5. SHELL-AND-TUBE HEAT EXCHANGERS

Shell-and-tube designs have the generalized form of LHTES systems most commonly deployed, which includes established manufacturing processes, scalability and compatibility with a range of aggrandizement approaches. These systems have the flows of HTF inside tube bundles and PCM on the shell-side that occupies the shell-side and allows large heat transfer areas and tolerable pressure drop properties [23, 24].

5.1 Design Methodologies

Complete design strategies of shell and tube LHTES have been established along with choices of materials, geometric choice, as well as, cost reduction. The epsilon-NTU (Effectiveness-Number of Transfer Units) method is a quick-performance approximation of preliminary design, which was tested and proved to correspond to experimental results [25]. This method assumes that there is HTF on the tube side, PCM on the shell side and that the phase change is arrived at through conduction, which gives conservative worst-case estimates with no consideration of any beneficial natural convection.

Genetic Algorithms (GA) optimization allows minimization of costs by changing tube diameter, tube number, shell diameter and length as long as the user specifications are not exceeded. Solar absorption chiller application case studies of solar absorption chiller had unit costs as low as USD 8,396 on 1.42 kW storage capacity by systematic optimization [26].

Table 3 contains design parameters of optimized shell-and- tube LHTES and the schematic of shell-and- tube LHTES configurations is presented in figure 3.

Table 3: Design Parameters for Optimized Shell-and-Tube LHTES.

Parameter	Range Studied	Optimal Value	Impact on Performance	Impact on Cost
Tube diameter	10–50 mm	25 mm	High	Medium
Tube number	10–100	45	Very High	High
Shell diameter	100–500 mm	300 mm	Medium	High
Tube length	1–5 m	2.5 m	High	Very High
Fin height	0–20 mm	12 mm	High	Medium
Fin spacing	5–30 mm	15 mm	Medium	Low

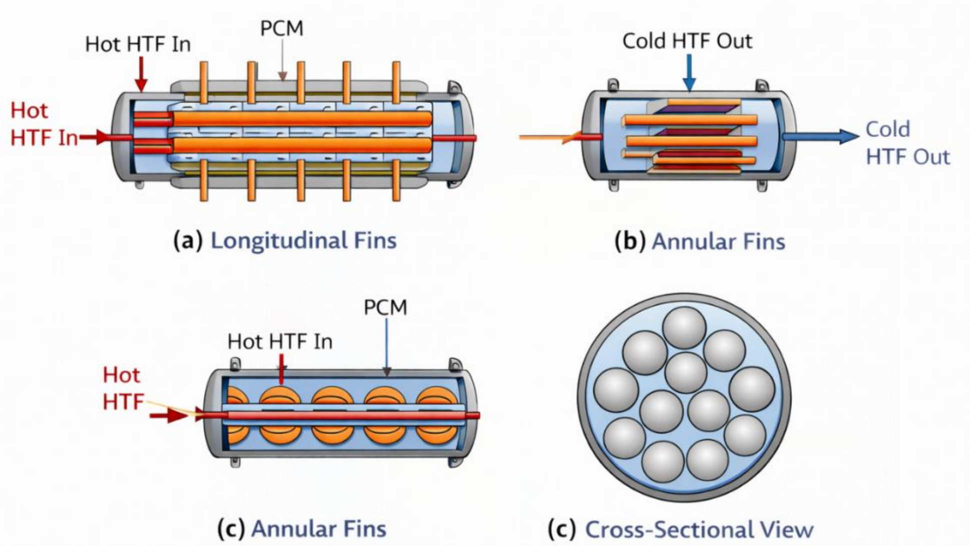

Figure 3: Schematic of shell and tube LHTES with longitudinal (a), annular (b) cross-sectional and (c) fins.

5.2 Enhanced Configurations

Designs Finned tube Shell-and-tube designs were found to be greatly enhanced by a finned tube construction. Centrifugal fins on tube arrests enhance the surface area whilst not changing the shell-side flow characteristics. It has been found that a fin diameter impact is greater than fin number or tube diameter on the heat transfer rates, where the optimal combinations exhibit 25 percent lower melting time [27].

Multi-tube designs are optimized in terms of tube layout (triangular, square or staggered pitch) which create a balance between the heat transfer and the use of PCM volume. The last recent research has delved into the study of variable tube diameters and different types of fin-tube to best use the geometry of fin-tube [28].

6. COMPUTATIONAL FLUID DYNAMICS (CFD) MODELING

Due to the ability of easily visualizing the process of transient melting front advancement, natural convection patterns, and temperature field development, Computational Fluid Dynamics has become invaluable to PCM heat exchanger design. More recent CFD methods use either enthalpy-porosity methods, phase-field methods or lattice Boltzmann techniques to address the moving-boundary problem of phase change processes [29, 30].

Modeling Approaches:

The enthalpy-porosity approach considers the mushy region to be porous and the porosity to range between 0 (solid) and 1 (liquid), so that it does not require explicit monitoring of the melting front. This method is a good way of modeling both natural convection at the liquid phase and conduction at the solid phase and it is confirmed to experiment with several fin geometries [31].

Table 4 displays CFD modeling strategy of PCM systems and figure 4 displays CFD simulation outcomes that exhibit (a) melting front as a time-dependent variable, (b) velocity vectors field in the course of melting, (c) temperature field, and (d) correlation with experimental outcomes.

Table 4: CFD Modeling Approaches for PCM Systems.

Method	Governing Equations	Computational Cost	Accuracy	Best Application
Enthalpy-Porosity	Single domain, phase fraction	Medium	Good	General melting/solidification
Phase-Field	Order parameter evolution	High	Very High	Microstructure evolution
Lattice Boltzmann	Mesoscopic particle distribution	High	Good	Complex geometries
Finite Element	Energy balance with phase change	Medium–High	Very Good	Stress-coupled problems
Machine Learning Surrogate	Data-driven approximation	Very Low	Medium	Real-time optimization

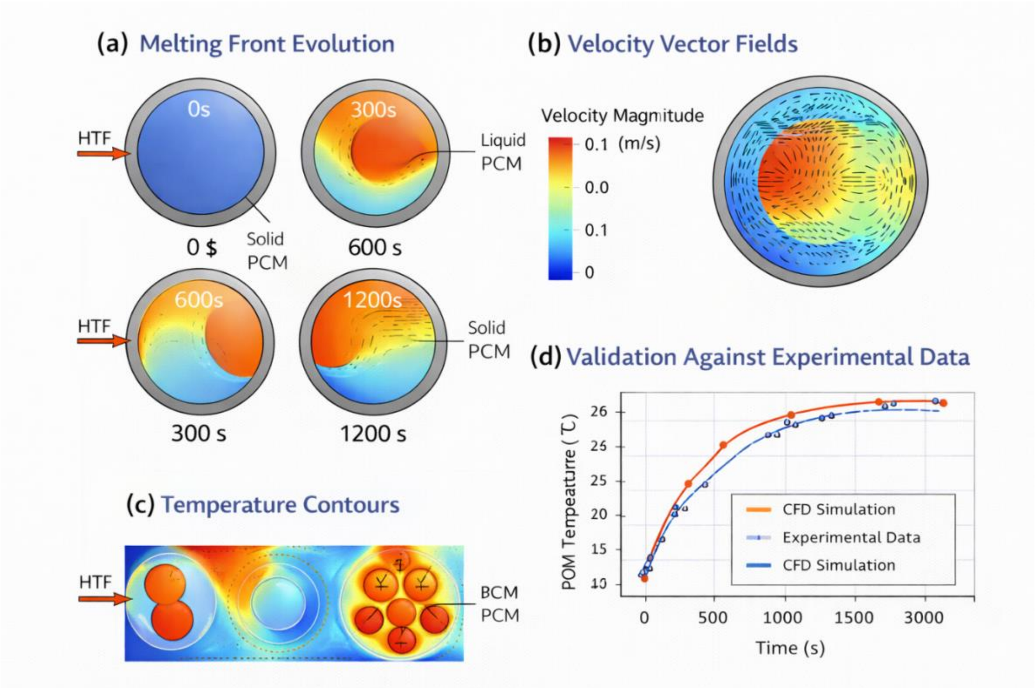

Figure 4: CFD simulation results showing (a) melting front evolution over time, (b) velocity vector fields during melting, (c) temperature contours, and (d) validation against experimental data.

6.1 Validation and Application

There is a large amount of experimental data which has been compared to CFD models of PCM melting in enclosures in different fin designs. The studies of optimization of tree-shaped fins applied validated CFD models to prove the decrease of 67% in melting time relative to unfinned enclosures, and the buoyancy effects were reasonably modeled [32]. The predictive nature of CFD allows parametric research into geometrical changes that can be inconvenient in experimental studies without the role of CFD.

Multi-Physics Coupling:

State-of-the-art CFD platform integrates fluid flow, heat transfer and solid mechanics to describe the effect of the thermal expansion, deformation of containers and development of stress within the container when trying a phase, change. These overall models facilitate estimation of long-term reliability and structural integrity of LHTES systems that are subjected to thermal cycling.

7. SOLAR THERMAL ENERGY STORAGE

The solar thermal power plant needs well-developed TES systems to ensure the production of electricity during the cloud transients and at night. PCM based heat exchangers have a high energy density with constant temperature heat delivery and can be used with the Rankine cycle power generation.

7.1 Central Receiver Systems

Smoothed-out solar power stations which employ molten salt PCM storage have proved to be commercially viable. Low thermal conductivity of molten salts is overcome by using hybrid enhancement methods such as high-temperature metal foams and lengthening surfaces. The recent research has investigated the cascaded PCM system in which the melting temperatures are more than one in order to achieve maximum exergy efficiency [33].

Table 5 presents specifications of solar thermal storage system and figure 5 presents schematic of solar thermal power plant that includes (a) molten salt storage, (b) PCM storage module and(c) temperature profile in both charging and discharging.

Table 5: Solar Thermal Storage System Specifications.

Parameter	**Molten Salt System**	**PCM System**	**Hybrid Enhanced PCM**
Operating temp. (°C)	290–565	300–400	300–400
Storage capacity (MWh)	100–1000	10–100	10–100
Energy density (kWh/m³)	70–80	100–150	120–180
Cost ($/kWh)	15–25	20–30	25–35
Round-trip efficiency (%)	93–95	85–90	88–92
Response time	Minutes	Seconds–minutes	Seconds

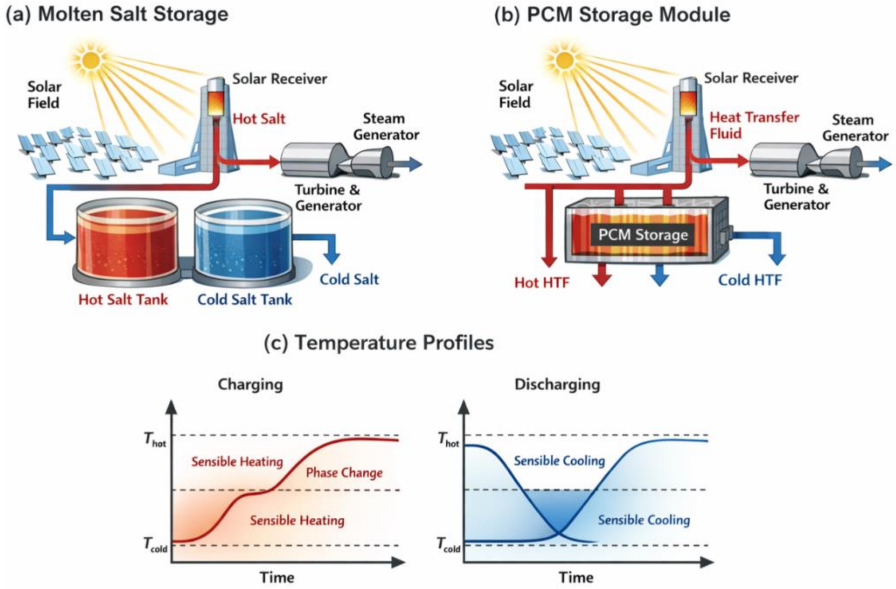

Figure 5: Schematic of solar thermal power plant with (a) molten salt storage, (b) PCM storage module, and (c) temperature profiles during charging/discharging.

7.2 Distributed Solar Thermal

PCMs are also used in construction solar thermal systems that are used to supply domestic hot water and space heating. Shell-and-tube LHTES transformed to suit the requirements of solar absorption chillers incurred USD 8,396/unit with power capacity of 1.42 kW, which proved to be economically viable [34].

8. COST-BENEFIT ANALYSIS

Hybrid-enhanced PCM heat exchangers have to be assessed in terms of incremental costs and benefits in terms of performance. The costs may consist of: (1) PCM material costs (organic: $1-5/kg, inorganic: $0.5-3/kg, specialized: $10-100/kg); (2) enhancement materials (nanoparticles: $50-500/kg, metal foams: $100-1000/kg); (3) manufacturing and containment costs; and (4) operating energy costs [35, 36].

Table 6 presents cost breakdown of hybrid PCM system, figure 6 presents cost breakdown pie charts (a) basic PCM system and (b) hybrid enhanced system; (c) cost comparison of levelized cost in storage technologies.

Table 6: Cost Breakdown for Hybrid PCM Systems.

Component	**Cost Range**	**% of Total (Basic)**	**% of Total (Hybrid)**
PCM material	$0.5–100/kg	30–40%	20–30%
Enhancement materials	$10–1000/kg	0%	25–40%
Containment/encapsulation	$5–50/unit	20–30%	15–25%

Component	Cost Range	% of Total (Basic)	% of Total (Hybrid)
Manufacturing	$10–100/unit	20–30%	15–25%
Installation	$5–20/unit	10–20%	5–10%

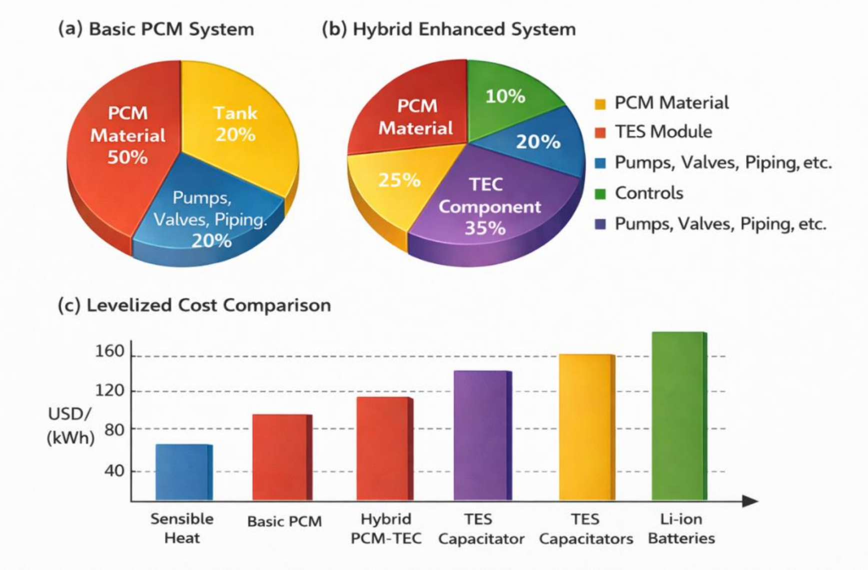

Figure 6: Cost breakdown pie charts for (a) basic PCM system and (b) hybrid enhanced system; (c) levelized cost comparison across storage technologies.

8.1 Levelized Cost of Storage

In-depth research has shown that, with an ideal shell-and-tube LHTES, costs are ranging between $50-200/kWh based on PCM type, enhancement methods, and size. Hybrid enhancement is 20-100% more expensive in initial cost but 100-500% more power density (kW/m^3) enhancing total system costs of power-sensitive systems [37].

9. Current Limitations

Regardless of the large steps that have been made, there are a number of obstacles limiting the widespread use of hybrid-enhanced PCM heat exchanger:

Long-Term Stability- Nanoparticle sedimentation, PCM chemical degradation, thermal cycling fatigue, and corrosion are of concern to 10-20 years City and industrial usage of the material [38].

Supercooling and Hysteresis: Part of the NePCM systems have high supercooling, it increases the delay in the initiation of the phase change and decreases the effective power density. Hysteresis during the melting and solidification decreases the efficiency of round trip.

Complexity in manufacture Hybrid systems with fins, foams and nanoparticles are complex to manufacture with problems in quality control. Additive manufacturing is a solution though it is still expensive when it comes to large-scale productions.

Standardization: The absence of standardized testing approaches and performance indicators make the comparison between studies and transfer of the technology to the industry difficult.

10. CONCLUSIONS

This survey has been able to take a systematic review of the state of art in Phase Change Material heat exchanger currently being used with special reference being given to hybrid thermal enhancement methods. It is determined in the analysis that hybrid strategies of integrating various enhancement techniques are more effective in general to isolated methods with the combination of metal foam-nanoparticle in the best case recorded 90 percent reduction of the melting time at a low energy density.

1. Hybrid Enhancement Superiority: Synergistic improvements due to combinations of metal foams with nanoparticles, or optimized fin geometries with NePCMs are better than the additive benefits of the individual techniques. The foam-nanoparticle hybrid consequence provides ideal performance-enhancement (80-90% reduction in melting time) and energy-density-retention (80-85%).
2. Geometric Innovation: Biomimetic fin designs, especially those in the form of a tree, or a bifurcated shape, is much more effective than traditional longitudinal or annular fin designs: the fin design encourages natural convection and increases the surface area to heat transfer. We find that topology optimization shows optimal geometries to be operating condition dependent, and should be application-specific, as opposed to universal.

The further development of materials should be directed towards sustainability, integration of additive manufacturing, adaptive systems which are smart, and standardized testing programs should be created to make advanced PCM-based heat exchangers commercializable.

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