

Impact of Fin Configurations on Thermal Charging in Latent Heat Thermal Energy Storage Systems: A Review

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Abstract

Latent heat thermal energy storage (LHTES) systems are widely used to overcome the mismatch between energy supply and demand in renewable and waste heat recovery applications. Phase change materials (PCMs) offer high storage density but suffer from low thermal conductivity, limiting their melting/solidification rates. Among different enhancement methods, finned structures have proven to be simple, effective, and economical for improving thermal performance. This review summarizes recent studies on the role of fins in LHTES systems, focusing on the influence of fin geometry, orientation, number, material, and placement on charging behavior. Various fin designs, such as annular, longitudinal, T-shaped, Y-shaped, fractal, stepped, and conical fins, as well as fin-heat pipe combinations, are discussed in relation to their ability to accelerate melting, improve heat transfer, and optimize system performance. The review highlights that proper fin design not only enhances charging rates but also reduces material use and system weight, making fins a practical solution for next-generation energy storage technologies.

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I. Introduction

Thermal energy storage (TES) systems have gained significant attention due to their vital role in advancing clean energy technologies and bridging the gap between renewable energy supply and demand. A notable example is the mismatch between solar energy generation and consumption, where TES can serve as an effective solution. These systems find extensive applications in solar thermal plants[1], waste heat recovery[2], district heating and cooling, power generation, and building energy management[3].

Incorporating PCMs in TES offers several advantages, including high energy storage density, superior heat transfer characteristics, and stable operating temperatures[4]. However, PCMs typically suffer from low thermal conductivity[5], which prolongs melting time and lowers system efficiency. To address this limitation, various enhancement strategies have been explored, such as integrating fins, embedding metal foams[6][7], introducing coil inserts[8], and dispersing high-conductivity nanoparticles[9]. Among these, fin-based configurations are particularly favored in LHTES systems due to their low cost, ease of installation, and ability to significantly boost thermal conductivity[4][10].

However, fins can sometimes negatively influence the development of natural convection within the melted PCM[11]. This restriction of fluid motion can diminish the beneficial impact of fins on heat transfer enhancement. Consequently, optimizing the geometric parameters of fins has become a key focus in designing LHTES systems that achieve higher efficiency, reduced weight, and more compact dimensions. Among various configurations, shell-and-tube heat exchangers (HXs) are particularly attractive for integration with practical LHTES units due to their simple design, high effectiveness, and ease of fabrication. In this context, the present study examines the solid-liquid phase change behavior in finned shell-and-tube HXs.

II. Influence of Fin Geometry and Configuration on LHTES Charging Performance

Researchers have explored the influence of different fin geometries—such as longitudinal[12][13], pin, helical[14][15], and annular fins[16][17] etc—on the thermal performance of PCMs in both horizontal and vertical orientations of shell-and-tube systems. Some researchers also designed the perforated fins. Perforated fins as shown in Fig.1, [18] designed with openings to allow fluid movement, enhance heat transfer in LHTES systems by minimizing the obstruction of natural convection. In a vertical shell-and-tube configuration, perforated fins increased the time-averaged Nusselt number by about 30% compared to solid fins. They also reduced total melting time by approximately 7%, owing to improved convection flow within the PCM.



Fig. 1 Perforated fins [18]

Similarly, Stepped fins as represented in Fig. 2, [19] designed with varying upward and downward geometries, enhance heat distribution in LHTES systems by directing heat flow more effectively within the PCM. Downward stepped fins with a step ratio of 0.66 achieved the best performance, transferring heat efficiently to the lower region and trapping it between the heated wall and fins. Compared to conventional horizontal fins, they accelerated melting by up to 56.3% at 800 s and 65.5% at 3600 s. Further, some researchers examined the impact of the fins distribution in the PCM.

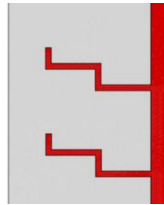


Fig. 2 Stepped Fins [19]

For example, In a horizontally oriented cylindrical double-tube LHTES unit with fins mounted on the inner tube, straight fins uniformly distributed around the circumference but without any parallel to the horizontal axis as outlined in the Fig. 3 achieved the shortest melting–solidification times compared to lower or angled fin arrangements [20]. Lower fins, positioned only in the lower half of the circle, enhanced melting but caused severe delays in solidification, particularly with increased fin length and number, making them less suitable where rapid discharge is needed. Angled fins, similar to straight fins but with two fins parallel to the horizontal axis, showed no significant advantage over straight fins. For the same fin volume, longer fins improved performance more than shorter ones, with fin geometry affecting solidification more than melting.

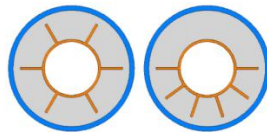


Fig. 3 Fins distribution [20]

Saeed Tiari et al. [21] investigated the influence of annular fins on the thermal performance of a shell-and-tube LHTES system positioned vertically as outlined in the Fig. 4. They analyzed different fin configurations, including twenty fins of uniform length and twenty fins of variable length. The study found that the most effective configuration for the charging process was twenty variable-length fins, arranged with longer fins at the bottom of the tube, which reduced the charging time by 73.7%. In contrast, the discharging process was optimized with twenty fins of uniform length, leading to a 79.2% reduction in discharging time. Considering both charging and discharging periods together, the configuration with twenty uniformly distributed fins was identified as the most efficient, yielding an overall time reduction of 76.3%.

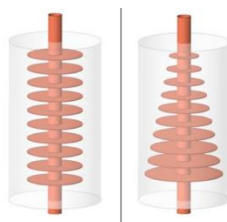


Fig. 4 annular fins [21]

Ahmed H. N. Al-Mudhafar et al. [22] investigated the enhancement of thermal performance in a shell-and-tube latent heat energy storage system by employing T-shaped fins and compared their effectiveness with traditional longitudinal fins as represented in the Fig.5. Four heat exchanger configurations were analyzed: without fins, with six T-shaped fins, with six longitudinal fins, and with six tree-shaped fins. The results showed that the system without fins achieved only about 15% PCM melting, whereas the use of T-shaped fins enabled 100% melting in a much shorter duration. Compared with longitudinal fins, the T-shaped fins reduced the overall melting time by 33%, clearly demonstrating that fin geometry has a decisive influence on PCM thermal performance.

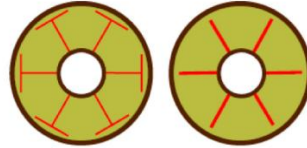


Fig. 5 different shapes of fins [22]

Jayesh Kumar et al. [23] conducted a numerical investigation on the influence of fin number and material, in combination with embedded heat pipes, for thermal charging in a trapezoidal LHTES container as indicated in the Fig.6. The study incorporated variable-length fins with three candidate materials: steel, aluminum (Al), and copper (Cu). The results indicated that although increasing the number of aluminum fins initially enhanced the performance ratio, the benefit gradually diminished with further fin addition. The configuration with twelve steel fins provided the most uniform temperature distribution within the system. Moreover, both the fin count and thermal conductivity were found to directly contribute to an improvement in mean power. Importantly, the cases with twelve copper fins and twelve aluminum fins yielded the lowest cost per unit mean power, while also demonstrating comparable performance, making them the most cost-effective options.

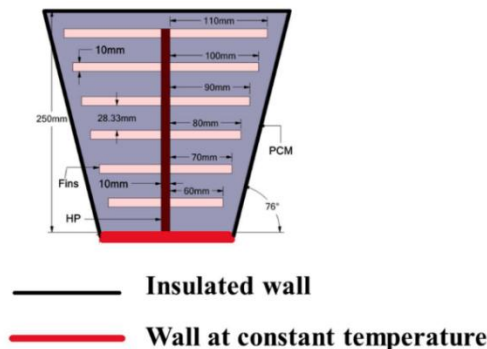


Fig. 6 fins with heat pipe[23]

Varun Joshi et al. [24] explored the optimal placement and sizing of fins to minimize the melting time in a latent heat thermal energy storage system for a given fin-to-PCM volume ratio. Numerical analysis revealed that using smaller fins in regions of low temperature gradient and repositioning them in areas of high gradient significantly improved performance. In this study, the fin-to-PCM volume was reduced by half which enhanced thermal performance by 4.38% compared to the conventional design. This reduction not only improved energy storage capacity but also lowered the fin mass, thereby decreasing the overall system weight. The study further concluded that fins should be avoided too close to the bottom surface to ensure uniform heat distribution throughout the enclosure.

Nidhal Ben Khedher et al. [25] investigated the use of circular Y-shaped fins in a vertically oriented shell-and-tube latent heat storage system as indicated in the Fig. 7. The study examined various geometric parameters, including stem length, tributary angle, and the number of Y-shaped fins. The findings indicated that increasing both the fin height and number, while decreasing the tributary angle, significantly improved system performance. In the optimized configuration, raising the Reynolds number of the heat transfer fluid from 500 to 2000 shortened the melting time by 31%, while increasing the inlet temperature from 45 °C to 55 °C further reduced the melting time by about 44%.

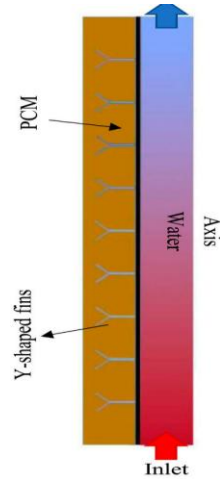


Fig. 7. Y shaped fins

Ming Zhao et al. [26] analyzed the effectiveness of fractal tree-shaped fins in latent heat storage (LHS) units and compared them with conventional plate fins as outlined in the Fig.8. The study revealed that fractal fins significantly enhanced both heat storage and heat release performance. With optimized fractal parameters, the system achieved superior results, showing a 35.85% faster melting rate and a 63.39% faster heat release rate compared to plate-fin configurations.

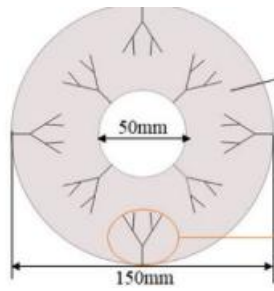


Fig. 8. Fractal tree-shaped fins

Hameed B. Mahood et al. [27] numerically investigated the effect of fin configuration on the melting of PCM in a horizontal shell-and-tube latent heat storage unit. A key challenge in such systems is that PCM at the bottom tends to remain solid due to the lack of natural convection, reducing overall thermal efficiency. To address this, different fin angles (72° , 60° , 45° , and 30°) were analyzed and compared against the baseline case of bare heat transfer fluid tubes as indicated in the Fig. 9. The results showed that increasing fin height significantly enhanced thermal performance. Reducing the fin angle further improved heat transfer, since fins positioned below the horizontal axis effectively targeted regions with poor melting. As a result, the melting time decreased by 6.7%, 14.3%, 16.7%, and 10.0% for fin angles of 72° , 60° , 45° , and 30° , respectively.

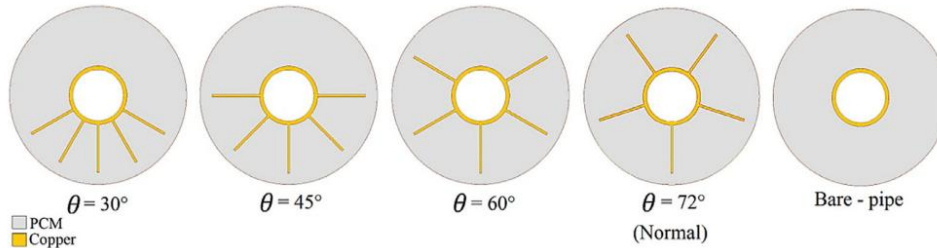


Fig. 9. Fins distribution[27]

Rupinder Pal Singh et al. [28] examined a conical shell-and-tube latent heat storage system (LHSS) with and without fins as outline in the Fig.10. The conical design utilizes natural convection more effectively by accommodating a larger amount of PCM in the upper region, resulting in a 16% reduction in melting time compared to a conventional setup. Furthermore, adding fins in the conical LHSS provided greater heat transfer enhancement than using nanoparticle dispersion.

S. E. Ghasemi et al. [29] studied a two-tube latent heat storage design to analyze the influence of fin number and length. The results showed that using two tubes and reducing the spacing between them significantly improved energy storage and shortened the melting time. Additionally, for a fixed number of fins, increasing fin length further reduced the PCM melting duration.

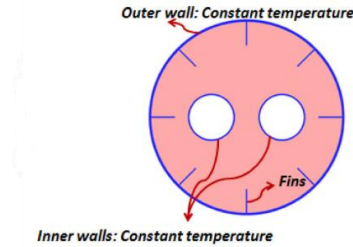


Fig. 10. Fins with two heat tubes[29]

Abduljalil A. Al-Abidi et al. [30] numerically investigated heat transfer enhancement in a triplex tube heat exchanger using internal and external fins for PCM melting. The study identified several parameters affecting melting time, including the number, length, and thickness of fins, and PCM unit geometry. Among the fin parameters, fin length and number had a much stronger influence on melting rate compared to fin thickness. Moreover, fully extended fins spanning from the inner tube wall to the outer shell achieved the fastest complete melting compared to other configurations.

Pascal Henry Biwolé et al. [31] analyzed phase change heat transfer in a rectangular enclosure with fins. The study found that thinner but longer fins improve performance, though longer fins increase stabilization time. At constant fin mass, changing fin spacing had little effect on latent heat storage or hot plate temperature stabilization. The results highlighted that surface area is the dominant factor enhancing heat transfer between the hot plate and PCM, while configurations that strengthen natural convection further improve heat flux.

Saeed Tiari and Songgang Qiu [32] studied a latent heat thermal energy storage system enhanced with finned heat pipes. Their findings showed that both the arrangement and number of heat pipes strongly influence system performance. Increasing the number of heat pipes reduced thermal resistance, accelerated the charging process, and lowered the base wall temperature. Furthermore, accounting for natural convection during charging further improved the melting rate and decreased the wall temperature.

Jayesh et al. [33] investigated the enhancement of part-load thermal charging in a latent heat storage unit using variable-length fins placed at optimized positions. The results showed that convective heat transfer plays a major role in PCM melting with variable-length fins. Under full-load charging, a uniform distribution of variable-length fins, with the longest fin positioned at the container base, achieved about 20% better performance than constant-length fins. However, during half-load charging, constant-length fins with uniform spacing reduced both the charging time and the average PCM temperature more effectively. Notably, Case VF-3 (fins placed only in the lower half of the container) showed the best thermal charging performance, achieving the fastest melting time for 90% charging of the system.

III. Discussion

From the literature, it is evident that fin geometry and arrangement critically determine the efficiency of heat transfer in LHTES systems. Variable-length fins at the bottom enhance charging due to stronger convection, while T-shaped and fractal fins outperform conventional longitudinal and plate fins. Y-shaped and stepped fins improve natural convection paths, reducing melting time significantly. Increasing fin height or number accelerates charging, though excessive fin addition may cause diminishing returns or restrict convection. Material choice also plays a vital role—copper and aluminum fins generally outperform steel, though steel can offer better temperature uniformity. Integration of fins with heat pipes has also shown remarkable potential in reducing thermal resistance and improving charging rates.

IV. Conclusion

This review highlights that fin-based enhancements remain one of the most effective strategies to improve the thermal charging of latent heat thermal energy storage systems. Key findings include:

Fin geometry (T-shaped, fractal, Y-shaped, stepped, and annular) significantly improves PCM melting compared to traditional longitudinal or plate fins.

Fin orientation and placement strongly influence performance: placing longer fins at the bottom or using fins only in high-temperature-gradient regions reduces melting time.

Fin size and number accelerate charging, though excessive fins can hinder natural convection. Optimal designs balance conduction and convection.

Fin material affects both cost and performance—copper and aluminum offer better conductivity, while steel provides uniform temperature distribution.

Hybrid systems (e.g., fins with heat pipes) further reduce thermal resistance and charging duration.

Overall, optimized fin configurations can achieve melting time reductions ranging from 15% to over 75%, demonstrating their critical role in designing efficient, lightweight, and cost-effective LHTES systems. Future research should focus on combining fin optimization with advanced techniques such as nanoparticles, metal foams, and hybrid storage designs to further enhance energy storage performance.

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