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Progress in the Study of Enhanced Heat Exchange in Phase Change Heat Storage Devices

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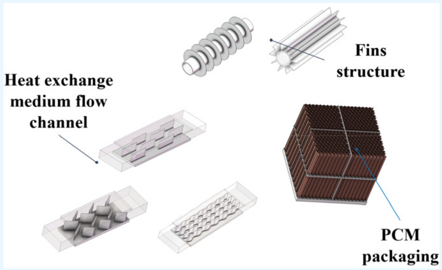
ABSTRACT: In comparison with sensible heat storage devices, phase change thermal storage devices have advantages such as high heat storage density, low heat dissipation loss, and good cyclic performance, which have great potential for solving the problem of temporal and spatial imbalances in the transfer and utilization of heat energy. However, there are also issues such as the small thermal conductivity of phase change materials (PCMs) and poor efficiency in heat storage and release, and in recent years, enhanced heat transfer in phase change thermal storage devices has become one of the research hotspots for optimizing thermal storage devices. Although there have been reviews of enhanced heat transfer technology for phase change thermal storage devices in the literature, there is still insufficient research on the summarization of the enhanced heat transfer mechanism, structural optimization, and applications of phase change thermal storage devices. This Review provides a review of enhanced heat transfer in phase change thermal storage devices from two aspects: internal structure enhanced heat transfer and heat exchange medium flow channel enhanced heat transfer. It summarizes the enhanced heat transfer measures of various types of phase change thermal storage devices and discusses the role of structural parameters in enhanced heat transfer. It is hoped that this Review will provide some references for scholars engaged in research on phase change thermal storage heat exchangers.



1. INTRODUCTION

With the advancement of technology and improvement of people's living standards, the demand for energy has greatly increased.[1] The excessive consumption of nonrenewable energy sources has led to the depletion of fossil fuels and the intensification of the greenhouse effect.[2,3] To address this issue, countries are actively seeking clean and renewable energy sources to reduce their dependence on fossil fuels. However, the availability of new energy sources, such as solar energy, can be inconsistent in time and location, making it necessary to store thermal energy for on-demand use.

Among various thermal storage technologies, PCMs offer the most promising thermal storage potential. They have high thermal storage density, readily available materials, and an isothermal phase change process.[4,5] They are widely used in fields such as aerospace, industrial waste heat recovery, and solar thermal utilization.[6,7]

In the aerospace industry, PCMs find significant applications in thermal control systems, life support systems, energy storage, and thermal protection systems. One notable use case is the utilization of PCMs to regulate the surface temperature of spacecrafts, safeguarding them against extreme temperature variations. Moreover, in life support systems, PCMs serve the purpose of storing and releasing heat, thereby ensuring a stable living environment for astronauts.

In the field of industrial waste heat recovery, PCM technology can be used in industrial process waste heat recovery, data center heat recovery, district heating and cooling, and other areas. By utilizing the properties of PCM to store and release heat, waste heat can be effectively recovered to improve the energy utilization efficiency, reduce energy consumption, and lower operating costs.

In the domain of solar thermal utilization, PCM technology finds applications in various areas, such as hot water supply, solar air conditioning systems, and solar thermal power generation systems. For instance, by utilizing PCM to store heat from solar energy, solar hot water supply systems can achieve efficient operation. PCM in solar air conditioning systems facilitates the absorption and release of heat, enabling air cooling and heating. PCM can store and release solar energy heat in solar thermal power generation systems, effectively generating electricity through steam turbine propulsion.

The application of PCM thermal energy storage systems has also become an important direction for the development of energy storage systems.

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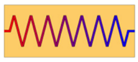
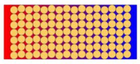
Table 1. Summary of Common Enhanced Heat Transfer Measures for Different Heat Transfer Structure Types

Heat exchanger type	Schematic	Commonly used enhanced heat exchange measures
Double tube type		Finished structure for enhanced heat transfer PCM package for enhanced heat transfer Media flow channel enhanced heat transfer
Three-tube type		Finished structure for enhanced heat transfer PCM package for enhanced heat transfer Media flow channel enhanced heat transfer
Spiral Coil Type		PCM package for enhanced heat transfer Media flow channel enhanced heat transfer
PCM package		PCM package for enhanced heat transfer
Board type		Media flow channel enhanced heat transfer
Enclosed		PCM package for enhanced heat transfer

Nevertheless, the majority of PCMs exhibit low thermal conductivity and energy absorption efficiency. To address this challenge, the design of the thermal storage device should aim to enhance the thermal conductivity of the PCM and optimize its heat exchange with the external fluid. Consequently, the internal and external heat transfer structures play a crucial role in enhancing the thermal storage efficiency of the PCM-based thermal storage system.

Despite numerous studies focusing on the individual heat exchange structures of phase change heat storage devices, further research is necessary to explore measures for optimizing heat exchange structures, mechanisms, and applications. This review presents a summary of the recent advancements in enhancing heat exchange measures in phase change heat storage devices from dual perspectives. Additionally, it offers relevant references for further research on phase change heat storage heat exchangers.[8] Table 1 provides an overview of heat exchanger types along with the corresponding enhanced heat exchange measures applicable to various heat storage equipment configurations. Within each figure, the yellow region represents PCMs, while the changing shades of red and blue depict heat transfer fluid (HTF). The table serves as a valuable reference resource tailored to researchers' specific requirements.

2. INTERNAL STRUCTURE TO ENHANCE HEAT EXCHANGE

Fins are commonly integrated into PCM to enhance heat transfer in phase change heat storage devices. Alternatively, the packaging method can be modified to increase the nominal thermal conductivity of the PCM.

2.1. Fins Structure. Directly attached to the outer wall of the runner, the fins enlarge the interface between the PCM and the heat exchange structure, leading to a substantial reduction in the melting and solidification time of the PCM. The fins integrated into the PCM are categorized into two types, namely, ring fins and straight fins, based on their connection to the outer wall of the runner. Figure 1 illustrates their structures, presenting three-dimensional diagrams of the ring fin structure (a) and straight fin structure (b) on the left and right panels, respectively.

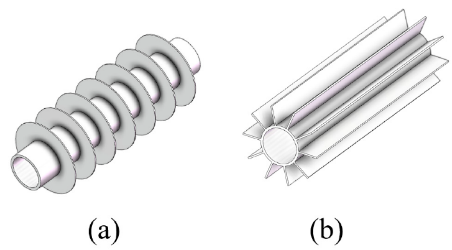


Figure 1. Ring fins and straight fins: (a) ring fins and (b) straight fins.

2.1.1. Ring fins. Ring fins are fins that encircle the working fluid pipeline radially and are aligned in the axial direction. The objective is to radially transfer the heat of the medium in the heat exchange pipeline into the interior of the PCM through the fins, thereby augmenting the nominal thermal conductivity of the PCM.[9] Nonetheless, the distinctive configuration of ring fins can give rise to concerns such as nonuniform melting of the PCM and impede the convection of the liquid-phase PCM.

In order to mitigate the issue of uneven melting of PCM in ring-fins energy storage equipment, Yang[10] devised nonuniform ring fins with varying fin spacing and positions. Experimental and numerical simulations revealed that the nonuniform distribution of ring fins with varying spacing settings enhanced the melting time by 62.8% and improved the melting uniformity by 84.7% compared to the utilization of uniform fins. Zhu[11] and Ghalambaz[12] investigated the ring fin structure with nonequal diameters and observed that augmenting the diameter of the bottom heat transfer dead zone ring fins enhanced the melting uniformity of PCM.

Guo[6,13,14] introduced a tubular corner fin design, characterized by an inclination angle between the ring fin and the HTF flow channel ranging from 0° to 75°. The findings indicated that the optimal performance was attained at an inclination angle of 10°, resulting in a 55.4% reduction in the melting time and a 20% enhancement in temperature uniformity upon full melting of the PCM.

Apart from the challenge of PCM melting uniformity, ring fins also impede the convection of liquid-phase PCM materials due to their structure, thereby impeding heat exchange. To overcome this issue, Karami[15] devised a perforated fin structure to investigate the melting process of PCM under varying working fluid flow rates and temperatures. Experimental findings revealed that the perforated fin structure exhibited minimal hindrance to thermal convection, resulting in a reduction in melting time by approximately 30% compared with conventional ring-fin structures.

Kalapala et al.[16] conducted a comparative analysis of the heat transfer performance of PCM heat storage devices with ring-fin structures at varying system inclination angles using experimental and numerical methods. The results indicated that during the initial melting stage of PCM, the melting rate remained consistent across all inclination angles. However, over time, the melting rate gradually declined, with a more pronounced decrease observed when the device was horizontally oriented. The vertically oriented device exhibited distinct advantages in terms of heat transfer efficiency.

Helical fins represent a distinctive variation of annular fins, capable of enhancing the convection of liquid-phase PCM and augmenting the nominal thermal conductivity of the material. Mehta et al.[17,18] conducted an analysis to examine the impact of helical fins on the heat transfer rate of energy storage devices. Figure 2 illustrates the helical structure under consideration. Experimental findings demonstrated a reduction in melting time of approximately 40% compared with conventional annular fins. Additionally, Mehta et al.'s experiments investigated the variation in the heat transfer capacity of the helical fin structure in heat storage devices at different inclination angles. The results indicated that the vertical orientation yielded the highest heat transfer efficiency. Ghalambaz[19] introduced a multihelical ring fin structure, which was further optimized by adjusting the number of helices, helix angle, and other parameters. The optimized multihelical ring fin structure exhibited improved temperature uniformity and contributed to a 42% reduction in melting time.

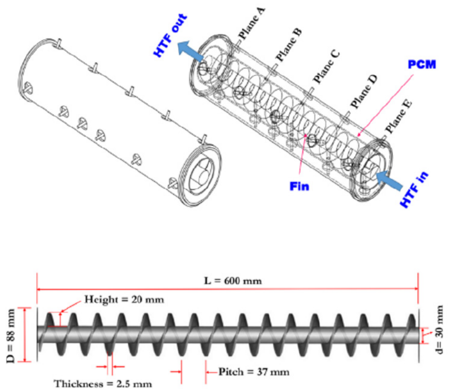


Figure 2. Schematic diagram of spiral fin.[18]

In summary, achieving efficient heat transfer from the heat exchange medium to the PCM is essential for effective operation of the phase change heat storage device. To accomplish this, fins can be incorporated into the PCM, or modifications can be made to its packaging method to enhance the nominal thermal conductivity. Various types of fins, including ring fins, straight fins, nonuniform ring fins, ring fins with nonequal diameters, and perforated fin structures, have been extensively investigated and optimized to enhance the heat transfer efficiency of the device. These optimizations encompass reducing the melting time of the PCM, enhancing its melting uniformity and minimizing hindrance to thermal convection. Moreover, the utilization of helical fins and multihelical ring fins has proven effective in enhancing the heat exchange performance of the device. In conclusion, enhancing the overall heat exchange efficiency of the device can be achieved by uniformly dispersing the heat within the PCM and facilitating convective heat transfer in the liquid-phase PCM.

2.1.2. Straight Fins. The term "straight fins" refers to fin structures that are axially attached to a pipeline and oriented radially. In contrast to "ring fins", the design of straight fins offers greater flexibility. By adjustment of the size and shape of the straight fins, it is possible to increase both the heat transfer area and the depth between the fins and the PCM.

A numerical study was conducted by Al-Mudhafar[20] to investigate the enhancement of thermal performance in a double-tube heat exchanger through the use of PCM. The study suggested using a T-shaped fin to enhance the depth of heat transfer within the PCM. Yan[21] proposed a Y-shaped fin structure for simulation analysis and found that reducing the fin thickness and increasing the bifurcation angle had a significant impact on reducing the melting time of PCM. Yao[22] introduced a triangular fin as an enhancement to the straight fin, aiming to achieve a more balanced heat distribution within the PCM. The results indicate a remarkable improvement in the melting efficiency of PCM by 30.98% compared to the conventional straight fin structure (refer to Figure 3.).

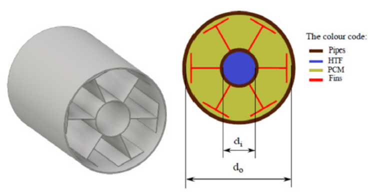


Figure 3. Structure of T-fin.[20]

The study conducted by Aly[23] focused on investigating the utilization of corrugated straight fins to improve the efficiency of heat exchange in heat exchangers. The researchers conducted a numerical simulation to analyze how the heat transfer performance is enhanced by varying the length of the fin and the angle between the line connecting the corrugated peak and the structural baseline. The findings demonstrated that the new corrugated straight fin structure outperforms ordinary straight fins by increasing the length of the fin and reducing the melting time of the PCM by 30−35%.

The dendritic fin structure, based on a similar principle, has been extensively investigated by numerous scholars. Figure 4 illustrates the dendritic fin structure. The multilayer distribution of dendritic fins creates a point-to-surface diffusion network for high heat flow, surpassing that of ordinary straight fins. Due to the stronger improvement in heat conduction relative to heat transfer compared to the inhibition of convection, this structure proves more effective in enhancing the melting rate and achieving uniformity in the temperature melting of PCM. Luo et al.[24,25] designed a range of heat exchangers featuring dendritic fin structures. The study analyzed and compared the solid−liquid interface, melting rate, and dynamic temperature changes in the dendritic heat

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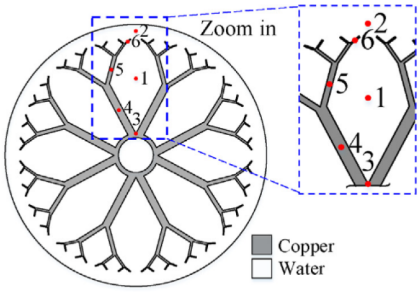

Figure 4. Section of tree fins.[27]

exchanger during the melting process with those of the ordinary straight-fin heat exchanger. Yu[26] determined the optimal fin-splitting angle, while Zheng[27] determined that the optimal number of tree-like fin layers is 4 using the transient model enthalpy-porosity method.

Notably, Boulaktout[28] and Chen[29] highlighted that heat conduction and heat transfer play a dominant role during the initial stage of PCM melting. The heat transfer at the fin level exhibits higher efficiency when the upper half of the PCM has melted, but it becomes less effective during the melting of the lower half of the PCM. Furthermore, under gravity conditions, the internal convective heat transfer becomes the dominant mechanism after the complete melting of the PCM. Consequently, apart from enhancing the nominal thermal conductivity of the PCM and promoting uniform PCM melting, it effectively enhances the heat exchange efficiency of the heat exchanger.

Taking this into consideration, Pahamli[30] developed an asymmetric design inspired by the aforementioned fin structure and introduced a novel configuration known as Blooming Straight Fins (BSFs), which are derived from T-shaped fins. The study examined the system performance by investigating several geometric parameters, such as the number of fins, fin compactness, fin height, and combined height of fins. The results revealed that modifying the number of fins and the density of fins resulted in a reduction in melting time by 17% and 2% respectively.

Additionally, Huang[31] developed an innovative hierarchical dendritic fin and introduced an asymmetric structure based on this design, as illustrated in Figure 5. The results indicate that this design can improve the melting rate by 35.9% compared to that of the standard dendritic fin.

Likewise, when the straight-fin heat exchanger is designed, it is essential to address the obstruction of convection within the PCM during the melting process. Ding[32] devised a perforated fin and conducted numerical simulations of the PCM melting process using the enthalpy−porosity model. The effectiveness of six fin designs was assessed by comparing the liquid phase fraction, melting time, and average temperature. The results demonstrate that the incorporation of perforated and slotted fins can alleviate the clogging effect and improve the melting rate.

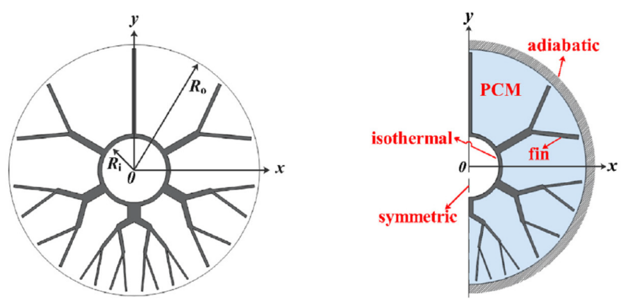

Figure 5. Structure of asymmetric dendritic fins[31]

Irrespective of the design, the objective is to enhance the thermal conductivity between the pipe and the PCM material. Table 2 presents a summary of the relevant research on enhancing heat transfer in finned structures.

In conclusion, extensive research has been conducted in recent years on finned structures to enhance heat transfer in PCM-based heat exchangers, leading to the proposal of various configurations of straight fins. These structures aim to enhance the heat transfer area and depth between the fins and the PCM while minimizing the internal convection obstruction during the melting process. Future efforts should focus on further developing the design of straight fins to enhance the thermal performance of the heat exchangers.

2.2. PCM Package for Enhanced Heat Transfer. The position and form of the PCM within a thermal storage device have a substantial impact on its thermal storage capacity. This review will assess three packaging structures employed in phase change thermal storage devices: cascaded latent heat storage, foam metal/nanoparticles, and capsules.

2.2.1. Cascaded Latent Heat Storage (CLHS). The temperature difference between HTF and PCM is a critical factor in determining the efficiency of the heat exchanger. If the flow channel of the HTF is lengthy or its speed is slow, the HTF temperature will decrease during the PCM melting process, resulting in a decrease in the PCM temperature as it moves away from the pipe. The arrangement of multiple PCMs with distinct phase transition temperatures and latent heat in a specific order within the heat exchanger is known as a CLHS configuration. This arrangement can enhance the heat storage capacity and heat exchange rate of the PCM.[33] This arrangement can be categorized as either series or parallel, depending on the relationship between the arrangement layer and the flow direction of the HTF. Figure 6 illustrates the structure where (a) represents a series configuration of CLHS, and (b) represents a parallel configuration of CLHS.

Elsanusi et al.[34] investigated the performance of CLHS with various series and parallel arrangements during the melting process. They also compared the performance of CLHS with single PCM heat storage devices. The research findings indicate that the parallel structure marginally improves heat conduction within the PCM, while it moderately inhibits thermal convection inside the PCM. On the other hand, the series structure enhances both thermal conductivity and convection. Both configurations can enhance the heat storage capacity of the heat exchanger by approximately 25% compared to a single PCM structure.

The CLHS in a series arrangement is positioned stepwise along the flow channel of the HTF. The average temperature of each PCM decreases sequentially in the direction of the HTF flow. However, as their phase change temperatures are arranged within the same range, the CLHS can undergo a simultaneous phase change, ensuring uniform melting throughout the CLHS in the heat exchanger.

Murthy[35] conducted a comparison of the heat transfer performance between conical CLHS (as depicted in Figure 7) and the traditional cylindrical model. The study specifically focused on the melting rate of the bottom part, which exhibits the slowest melting within the tube and shell unit. The results

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Table 2. Heat Transfer of Enhanced Fin Structure

Reference	PCM	Type of Research	Fins type	Key structures/ variables	Optimization Principle	Examining parameters	Efficiency gains
Yang[10]	Paraffin wax	Experimental Numerical	Ring fins	Fins position and spacing	Optimized melting uniformity	Melting time Average temperature difference	62.8% 84.7%
Zhu[11]	RT35	Numerical	Ring fins	Fin radius	Optimized melting uniformity	Melting time Average	10%
Ghalambaz[12]	Coconut Oil	Numerical	Ring fins	Fin radius	Optimized melting uniformity	Melting time Average	20%
Guo[6,13,14]	Paraffin wax	Experimental Numerical	Ring fins	Fins angle	Optimized melting uniformity	Melting time Average temperature difference	55.41% 20%
Karami[15]	Lauric acid	Experimental	Ring fins	Perforated fins	Reduced convective obstruction	Melting time	7%
Mehta[17,18]	Stearic acid	Experimental Numerical	Spiral Fins	Fins pitch System tilt angle	Optimize PCM convection without changing the thermal conductivity area	Melting time Solidification time	41.48% 22.16%
Kalapala[16]	Lauric acid	Experimental Numerical	Ring fins	System tilt angle	Optimized PCM convection	Melting time	42.81%
Al-Mudhafar[20]	RT82	Numerical	Straight fins	T-fins structure	Increase the dimension of thermal conductivity direction	Melting time	33%
Yan[21]	RT82	Numerical	Straight fins	Y-fins structure	Increase the dimension of thermal conductivity direction	Melting time	34%
Yao[22]	Li_2CO_3−K_2CO_3−Na_2CO_3	Numerical	Straight fins	Triangular fins	Increase the dimensionality and uniformity of the thermal conductivity direction	Melting time	30.98%
Aly[23]	Formic acid	Numerical	Straight fins	Serrated corrugated fins	Increase the contact area between fins and PCM	Solidification time	30−35%
Yu[26]	Lauric acid	Numerical	Straight fins	Dendritic fins	Increase the dimension and depth of the thermal conductivity direction	Melting time	26.7%
Zheng[27]	Water	Numerical	Straight fins	Dendritic fins	Increase the dimension and depth of the thermal conductivity direction	Melting time	53%
Luo[24,25]	Lauric acid	Numerical	Straight fins	Dendritic fins Combination Type	Increase the dimension and depth of the thermal conductivity direction	Melting time	68%
Huang[31]	RT82	Numerical	Straight fins	Tree-like structure Asymmetric structure	Increase the dimension of heat conduction direction to improve melting uniformity	Melting time	41.1%
Pahamli[30]	RT35	Numerical	Straight fins	Flower fins Asymmetric structure	Increase the dimension and depth of the thermal conductivity direction	Melting time	15%
Ding[32]	Paraffin wax	Numerical	Straight fins	Perforated fins Slit fins	Optimize PCM convection without changing the thermal conductivity area	Melting time	14.1%
Boulaktout[28]	n-eicosane	Numerical	Straight fins	Fins direction System Tilt	Optimized PCM convection	Melting time	10.1%

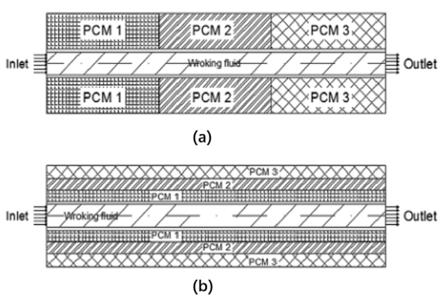

Figure 6. Multistage phase change structure in series and parallel: (a) CLHS in series and (b) CLHS in parallel.[34]

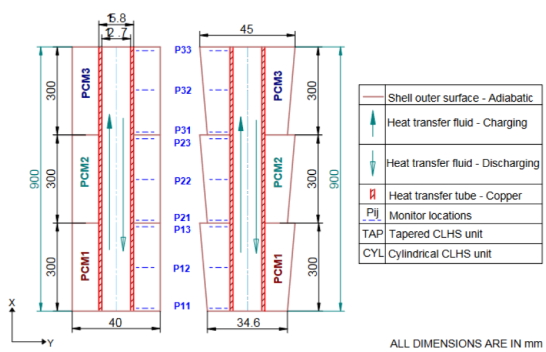

Figure 7. Pyramidal M-PCMs structure.[35]

showed that the conical model significantly enhanced the melting rate of the PCM by utilizing convection heat transfer. Initially, Sodhi[36] examined the heat storage efficiency of a system incorporating three identical PCMs combined with nonuniform fins. Subsequently, the series CLHS was combined with nonuniform fins, leading to a reduction in the melting and

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ACS Omega 2023, 8, 22331−22344

solidification time of the PCM in the system by 30% and 9%, respectively.

Furthermore, while the multistage PCM package significantly enhances melting uniformity, it does not enhance thermal conductivity within the phase change material. Moreover, the optimal configuration of the multistage PCM varies under different operating conditions. Hence, to maximize the performance of the phase change heat storage device, coupling the multistage PCM package with other enhanced heat transfer methods is often necessary.

Li[37] introduced a novel thermal energy storage approach that utilizes CLHS to mitigate thermal energy losses in an adiabatic compressed air energy storage system. They conducted a comprehensive analysis of the thermal storage performance of this specific heat accumulator by developing a mathematical model. The findings revealed a 51% increase in the heat storage efficiency of CLHS compared to a single PCM, while it experienced minimal heat energy loss.

In the parallel CLHS configuration, the PCM is arranged in stages along the radial direction of the HTF to account for the radial temperature gradient during the heat exchange process. The arrangement of the PCM in multiple stages along the radial direction facilitates enhanced heat conduction and ensures the uniform melting of the PCM within the heat exchanger. However, it is important to consider the potential hindrance to natural convection within the heat sink, which may arise from the separation of PCM layers by the metal wall. To mitigate this issue, Xu[38] employed straight fins to connect each layer of PCM, as depicted in Figure 8, and conducted a comparative analysis of the heat exchange effects across various fin connection structures. The findings revealed that the inclusion of fins significantly reduced the melting time of the PCM. Notably, cases 4 and 8 exhibited enhanced thermal conductivity between the layers, resulting in the most optimal heat transfer performance.

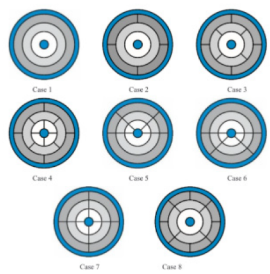

Figure 8. Multistage PCM built-in fin.[38]

Besides the inclusion of built-in fins, the incorporation of porous media materials during PCM packaging has a substantial influence on enhancing its nominal thermal conductivity. Soukht[39] and Pu[40] and other researchers have conducted studies to evaluate the melting performance of PCMs in ternary double-sided heat exchangers. The results indicate that three-layer PCMs have a slower melting rate compared to that of single-layer PCMs, but the incorporation of porous media materials enhances the melting rate of three-layer PCMs.

In conclusion, incorporating CLHS in heat exchangers yields enhanced performance compared with single-PCMs, especially when arranging the PCMs in series based on their phase change temperatures. Varied inlet fluid velocities exert a significant influence on the performance of CLHS heat storage systems, and researchers have been exploring the optimization of heat exchanger performance by meticulously selecting combined PCMs and determining their volume fractions. Table 3 provides a summary of recent studies on packaging CLHS.

In addition to double-tube and three-tube phase change thermal storage structures, researchers are also exploring flow channels as an alternative solution to the problem of PCM uneven melting. Nevertheless, it is important to take into account the effects of altering the PCM arrangement on the thermal storage capability of the system and the HTF maintaining the reverse flow direction during the exothermic and thermal storage processes. The optimization of the volume fraction of each component in CLHS through a judicious selection of combined PCMs is a significant area of current research in this field.

2.2.2. Porous Media Structure. Foam metal consists of a framework and numerous densely packed clusters of small voids. Utilizing foam metal with high thermal conductivity as an enclosure for PCM can significantly enhance the nominal thermal conductivity of PCM and bolster the heat transfer capability of PCM-based heat storage devices.[44]

Li[45] conducted experimental and numerical studies on the melting phase transition of paraffin in foam metal, and the results showed that, although the high thermal conductivity foam metal inhibited local natural convection, it more effectively enhanced the melting heat transfer. Prasanth[46] compared the melting times of PCM−aluminum wire braided foam and PCM−copper foam. The results show that the melting times of the two are comparable, and their thermal efficiencies are 60−70% and 80−85%, respectively.

Esapour[47] employed RT35 as the PCM to conduct a numerical simulation of the melting and solidification process within foamed metal in a multitube heat exchanger. The findings revealed that the incorporation of foamed metal packaging can substantially enhance the melting and solidification rates when compared to PCM without foamed metal. Fteiti[48] discovered that foamed metals with random porosity exhibited approximately 10% higher thermal conductivity compared to those with uniform porosity. Cui[49] and Wang[50] employed numerical simulation and artificial neural networks prediction methods to investigate the coupling structure between metal foam and fins, establishing a numerical model that was validated through experimental system verification. The results indicate that optimizing the metal foam−fin coupling structure can reduce the melting time, improve heat transfer performance by increasing the number of fins, and minimize heat accumulation in the upper region.

However, it is important to note that the density of the foam metal is generally significantly higher than that of phase change materials. Consequently, the addition of foam metal often leads to an increase in the weight of the device, making it unsuitable for scenarios with strict lightweight requirements.

Han[51] conducted an experiment by adding 3% volume fraction of Al_2O_3 nanoparticles to PCM and observed a significant improvement in the melting performance and a 15% reduction in melting time. Zhou[52] investigated the impact of nanoparticles, including CNT, Cu, and Al_2O_3, on the melting process of PCM under microgravity conditions. They found that CNT was more effective in enhancing the phase transition of *n*-octadecane. NematpourKeshteli[53] performed numerical simulations of PCM melting in a three-tube heat exchanger using various methods such as foam metal and nanoparticles.

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ACS Omega 2023, 8, 22331−22344

Table 3. Application Research of Multilevel PCM

Reference	PCMs	Type of Research	Joint level approach	Key structures/variables	Examining parameters	Enhance efficiency
Elsanusi[34]	Binary eutectic salt (not real material) (not real material)	Numerical	Series/parallel connection	Comparison of series and parallel connection methods	Melting time Heat storage capacity	15.5% 25%
Murthy[35]	OM42 OM46 OM48	Numerical	Tandem	Tapered tube housing	Melting time	2.4%
Zhang[41]	RT60 RT55 RT50	Numerical Experimental	Tandem	Concentric/eccentric pipes Foam metal	Commentary (Thermal efficiency)	28%
Li[37]	RT67 RT107	Numerical	Tandem	Capsule encapsulation Multiple cycles	Commentary (Thermal efficiency)	51%
Sodhi[36]	(not real material) (not real material) (not real material)	Numerical	Tandem	Segmented tandem Nonuniform ring fins	Melting time Solidification time	30% 9%
Xu[38]	RT42 RT50 RT60	Numerical	Parallel connection	A variety of fins	Melting time Heat storage density	71.4% 36.2%
Soukht[39]	(not real material) (not real material) (not real material)	Numerical	Parallel connection	Foam metal	Melting time	27.1%
Pu[40]	RT60 RT55 RT50	Numerical Experimental	Parallel connection	Foam metal	Melting time	23.7%
Mozafari[42]	RT55 RT60 RT65	Numerical	Parallel connection	Eccentric runners	Melting time Solidification time	23.43% 18.87%
Moghaddam[43]	RT50 RT82	Analysis	Parallel/Series	HTF Parameters Nanoparticles	Melting time	10−18.5%

The results demonstrated a reduction in melting time by 69.52% and 53.17% for foam metal and nanoparticle packaging, respectively, compared to that of pure PCM packaging, leading to a significant improvement in heat storage and discharge efficiency. Mahdi et al.[54] investigated the application of composite porous foam/nanoparticle enhancement technology. They developed a mathematical model that considered the effects of the porous foam and nanoparticles. The study demonstrated that the combined action of foamed metal and nanoparticles can reduce the melting time of phase change materials by up to 90%.

Additionally, there are packaging methods, such as anisotropic porous skeletons and aerogel skeletons. These methods share a similar principle to foam metal, as they effectively enhance the nominal thermal conductivity of PCM. The former refers to a skeleton structure with varying void sizes and distribution densities in all directions,[55] while the latter denotes a relatively stable composite material incorporating PCM.[56,57]

In conclusion, exploring the synergistic effects of high-porosity porous media, low-volume fraction nanoparticles, and fins, along with other heat transfer enhancement techniques, is crucial in maximizing the system performance while minimizing PCM volume occupancy and promoting natural convection during the melting process. This research direction holds significant importance for future investigations.

2.2.3. Capsule Structure. Encapsulating PCM with capsule packaging is a widely used method that offers various benefits such as improving the nominal thermal conductivity, preventing leakage, simplifying packaging, and enabling stable and efficient storage and release of thermal energy. Wang[58] introduced a microencapsulated phase change material composed of alloy and ceramic, which effectively utilizes the latent heat of the phase change material as well as the high thermal conductivity of the alloy/ceramic. Majumdar[59] conducted an analysis of the heat transfer model between an unbalanced PCM and HTF, compared it with published experimental results. The study determined the optimal performance of the PCM thermal storage device by considering factors, such as the height of the thermal storage layer and the diameter of the capsules.

Additionally, Gao et al.[60] incorporated spherical large capsules filled with low-melting-point metal (LMPM) into a convective cooling radiator as a PCM. The research examined the impact of various accumulation modes, particle diameters, and inlet velocities on the enhanced heat transfer within the packed bed. The findings indicated that the composite radiator, utilizing LMPM-PCM large capsules, exhibited improved thermal management performance in comparison to that of a conventional convective cooling radiator. Specifically, it reduced the temperature increase caused by pulse heat loads by 73.4%, highlighting the advantages of employing spherical particles.

In summary, the utilization of filling and packaging techniques, such as foam metal, nanoparticles, and capsules, plays a crucial role in enhancing the thermal efficiency of phase change thermal storage devices. Recent studies on foam metal and capsule packaging are compiled in Table 4. It is believed that besides investigating the influence of variables like foam metal porosity, nanoparticle specific gravity, and capsule radius on the nominal thermal conductivity of PCM, the versatility of

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Table 4. Study on Foam Metal and PCM Encapsulation

Reference	PCM	Package Type	Type of Research	Heat exchanger type	Key structures/variables	Examining parameters	Enhance efficiency
Prasanth[46]	Paraffin wax	Foam metal	Experimental	Enclosed	Aluminum foam wire/ copper foam	Melting time	23.2%
					Change to water/air as medium	Thermal storage efficiency	−30% to 15%
Chen[61]	Paraffin wax	Foam metal	Numerical	Board type	PCM/Foam & HTF/ Foam	Melting/solidification time	84.9%
					Change of foam metal porosity		
Esapour[47]	RT35	Foam metal	Numerical	Three-tube type	Change of foam metal porosity	Melting time	50%
						Solidification time	33%
Cui[49]	RT28	Foam metal	Numerical	Enclosed	Change the porosity of metal foam	Fo × Ste	\
					The number of fins coupled		
Wang[50]	Octadecane	Foam metal	Numerical	Three-tube type	Change the porosity of metal foam	Melting time	\
					The number of fins coupled		
Han[51]	RT82	Nanoparticles	Numerical	Three-tube type	Change the specific gravity of nanoparticles	Melting time	15%
Zhou[52]	Octadecane	Nanoparticles	Numerical	Enclosed	Change the type of nanoparticles	Melting time	\
NematpourKeshteli[53]	RT42	Foam metal	Numerical	Three-tube type	Change of foam metal porosity	Melting time	69.52%
		Nanoparticles			Changing the specific gravity of nanoparticles		53.17%
Mahdi[54]	RT82	Foam metal	Numerical	Three-tube type	Change of foam metal porosity	Melting time	90%
		Nanoparticles			Changing the specific gravity of nanoparticles		
Majumdar[59]	OM48	PCM capsules	Experimental	Enclosed	Capsule diameter	Melting time	54.6%
			Numerical				
Gao[60]	E-	PCM capsules	Experimental	Enclosed	Capsule diameter	The temperature difference between the entrance/exit	\
					Capsule stacking method		
					Capsule material		
Shin[62]	*n*-octadecane Paraffin wax	Microencapsulated phase change slurry	Experimental	Tube Sleeve Type	Spiral fins structure	Heat transfer efficiency per unit flow rate	180%

packaging forms can expand the applicability of phase change heat storage to various heat storage requirements.

3. HEAT EXCHANGE MEDIUM FLOW CHANNEL REINFORCED HEAT EXCHANGE

Compared with the built-in fin and package structure, the flow channel of the HTF is another critical factor that determines the heat exchange performance of a PCM heat storage device. Various heat exchanger structures have different forms of flow channels. Two main approaches can enhance the heat exchange efficiency of the runner: increasing the heat exchange area between the runner and PCM and improving the convection of the medium within the runner.

3.1. Pipeline Structure. The double-, shell-, and three-tube heat exchangers utilize circular pipes as their flow channels. This paper primarily provides an overview of the pipe section shapes, spiral pipes, and number of pipes employed in these heat exchangers.

3.1.1. Pipe Section Shape. The efficiency of heat exchange between the HTF and heat exchanger is determined by the structure of the HTF flow pipe. However, variable section pipelines typically have a more complex structure and higher production costs. Additionally, due to their structural characteristics, cleaning variable section pipelines is more challenging. Prolonged periods without cleaning can result in the accumulation of dirt and sediment within the tubes, thereby impacting the efficiency of heat transfer.

Corrugated pipe can enhance the heat transfer area but also, through the corrugated structure, strengthen the convection inside HTF, thus improving the heat transfer capacity of the heat exchanger. Shahsavar[63,64] conducted thermal performance analysis on two-tube bellows phase change heat exchange units during melting and solidification, while Shahsavar performed a similar analysis on three-tube units. The results revealed that increasing the amplitude led to shorter melting and solidification times. Keshteli[65] investigated the solidification process of PCMs and discovered that introducing wave-like patterns to the pipes can decrease the melting and solidification time. Mazhar[66] analyzed numerical models of bellows fin heights and pitch lengths at various mass flows to evaluate the melting and solidification of PCM heat storage. The results demonstrated that the flow and heat transfer performance were significantly enhanced with a bellows fin height of 4.5 mm and a pitch of 30 mm.

Besides the bellows structure, twisting the pipe is an alternative method to modify the pipe section's shape and enhance the heat transfer capacity of the heat exchange medium. Fallah et al.[67] conducted the design and analysis of a thermal storage structure containing PCMs, which consisted of a spiral double-shaped pipe. The results indicated that the heat transfer performance was optimized when using a 3-petal torsion section.

In conclusion, altering the cross-sectional shape of the pipeline aims to create continuous turbulence within the working fluid, resulting in a thinner overall boundary layer and enhancing convective heat transfer between the working fluid and the pipeline.

3.1.2. Spiral Pipe. Besides modifying the shape of the pipe section, the helical arrangement of pipes within the device can enhance the heat exchange performance. The helical arrangement of the HTF pipes enhances the heat exchange area between the HTF and the PCM while maintaining a constant flow rate at the inlet and outlet.

Researchers such as Saydam[68] and Punniakodi[69] have developed spiral coil type PCM heat storage devices and conducted analyses on their heat storage performance under various conditions. These studies have demonstrated that the use of spiral pipes can greatly enhance the uniformity and speed of PCM melting. These studies have demonstrated that utilizing spiral pipes can greatly enhance the uniformity and speed of PCM melting. Afsharpanah[70] further discovered that connecting spiral pipes with a high thermal conductivity metal plate in the axial direction (as depicted in Figure 9) substantially enhances heat transfer efficiency, leading to a 25.26% improvement.

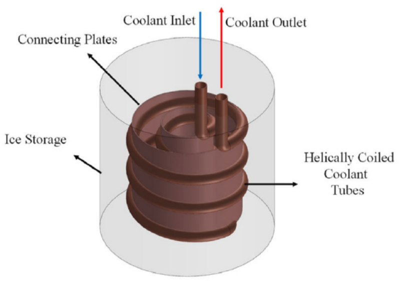

Figure 9. High thermal conductivity metal plate connected with spiral tube.[70]

Ardahaie[71] conducted a study on a flat spiral tube heat exchanger, as depicted in Figure 10. Numerical simulations were conducted by him on variables, including the mass flow rate and inlet temperature of the HTF. These simulations were conducted to analyze the influence of parameters such as the number of coils in each flat spiral tube plane (FSTP), the inclination angle of the shell, and the distribution of FSTP throughout the shell. The results indicated that an uneven distribution of spiral pipes within the shell significantly affects the optimization of the melting and heat transfer processes. Moreover, Ardahaie[72] conducted a numerical study on the storage performance of a porous metal hydride storage tank that incorporates PCM as a passive heat transfer system. The research revealed that conical PCM containers demonstrated a superior heat transfer performance.

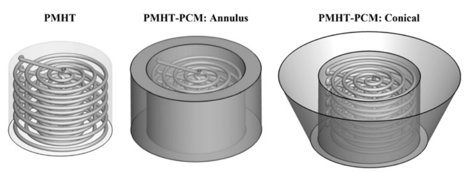

Figure 10. Structure of flat-plate spiral tube heat exchanger.[71]

Furthermore, the study investigated the optimization effect of the spiral coil structure on the heat exchange capacity of the heat exchanger, considering factors such as the diameter, angle, and density of the spiral coil.

In conclusion, the spiral tube structure, in addition to increasing the heat exchange area between the working fluid and the heat exchanger, enhances the internal capacity of the PCM heat storage device due to its unique structure as opposed to simply modifying the pipe section.

3.1.3. Number of Pipes. Double-tube and three-tube heat exchangers possess a simple structure and are easily manufactured. However, the heat exchange between the HTF and the heat storage device is insufficient due to the presence of a single flow channel structure. Consequently, the inclusion of additional HTF pipes has emerged as a viable solution to address this limitation.

Joybari et al.[73] conducted an experimental study on a vertical cylindrical phase change heat storage device with multiple tubes. The results indicate that the multitube heat storage structure exhibits shorter heat storage and release times compared to the single-tube heat storage structure. Specifically, the multitube structure enhances the contact area between the HTF and the heat exchanger without altering the HTF flow rate, resulting in improved heat exchange efficiency.

However, the optimization of the heat transfer effect is currently limited to a mere increase in the heat transfer area. Furthermore, further research will explore the combination of the multitube structure with other measures mentioned above to enhance heat transfer. For example, Kiribcic[74,75] conducted a study on the melting and solidification process of a shell-and-tube phase change heat storage device equipped with straight fins. They developed an accurate descriptive model of the heat storage and release processes and conducted comparative calculations using Fluent software. The results indicate that the heat dissipation performance of the multirunner heat exchange structure with straight fins is more favorable for enhancing the heat exchanger's heat dissipation performance and improving heat exchange efficiency.

The three-tube phase change thermal storage structure offers a significant advantage over the single-tube structure due to its larger heat transfer area per unit length and higher overall flow rate in the annular area, thereby enhancing the heat exchanger's heat exchange efficiency.

Esapou[47] conducted a numerical study on the melting and solidification process of PCM in a variety of flow channel structures designed based on the three-tube heat exchanger. The integration of foam metal into the PCM was also investigated. The findings indicate a 41% increase in melting efficiency and a 23% increase in solidification efficiency through the multichannel design of the inner tube. Furthermore, webbed fins were introduced in the Al-Mudhafar[76] multichannel structure to connect the inner tube with the outer ring, resulting in notable enhancements. A comparison with the conventional three-tube structure revealed significantly improved melting and solidification efficiencies along with a 41% acceleration in the solidification process.

Shell and tube heat exchangers, depicted in Figure 11, are widely used in industrial heat exchange equipment among various multitube structures. Riahi[77,78] conducted a discussion and comparison of the characteristics and behavior of PCM in

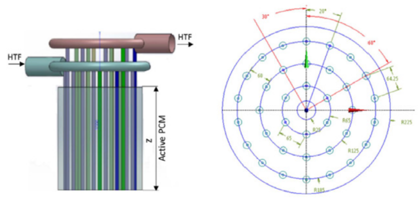

Figure 11. Structure of shell and tube heat exchanger.[77]

different shell and tube configurations, namely vertical countercurrent and horizontal parallel flow. The findings indicate that the vertical plate fin configuration maximizes the available heat.

Additionally, it is important to consider that an increase in the number of pipes will increase the maintenance cost of the equipment. Furthermore, a multipipe structure can impede the flow within the PCM to some extent; therefore, more pipes do not necessarily yield better results.

In addition, the increase of pipes will increase the maintenance cost of the equipment, and the multipipe structure will hinder the flow inside the PCM to a certain extent, so the number of pipes is not the more the better. We believe that while increasing the number of pipes, it will also reduce the packaging volume of the PCM. For this reason, the changes in the volume of the PCM should be taken into account when conducting research and the optimal pipeline arrangement should be found on the basis of it. Table 5 summarizes the research related to the HTF pipeline structure.

3.2. Other Runner Structures. Various heat exchanger structures exhibit different flow channel configurations for the HTF. Apart from tubular flow channels, studies have also explored plate-type, plate-fin-type, microheat pipe, and other structural heat exchangers.

The plate heat exchanger consists of heat exchange plates separated by rubber strips. Its complex structure and high flow resistance restrict the enhancement of heat exchange efficiency, leading researchers to concentrate on improving the performance of such heat exchangers. Santos[79] devised a novel plate design for plate heat exchangers and conducted a comparative study using computational fluid dynamics (CFD) against the existing design. The findings demonstrated that the new design doubled the heat exchange efficiency, increased material usage by 13.7%, and effectively mitigated the pressure drop caused by the fan. Gürel[80] performed numerical simulations to investigate the solidification process of PCMs in plate heat exchangers employing latent heat energy storage technology. They examined the melting process across three distinct plate types under varying HTF temperatures, steel plate thicknesses, and PCMs. The results indicated a reduction in the melting time by 63%.

Plate-fin heat exchangers typically consist of baffles, fins, seals, and deflectors. Interlayers, composed of fins, deflectors, and seals, are positioned between two adjacent baffles and stacked to form a plate bundle that serves as the core of the plate−fin heat exchanger. The heat exchange capacity of the plate-fin heat exchanger can be enhanced by incorporating PCMs into the plate−fin structure and filling the serrated space with PCM. Talebizadehsardari[81] developed a sawtooth model of the plate−fin heat exchanger to investigate the impact of the sawtooth angle on the melting rate of PCM. The findings revealed that a 60° sawtooth angle yielded the best results. Mahani et al.[82] improved the thermal storage structure of PCM in corrugated (serrated) plates and conducted numerical studies on melting and solidification. The flow channel structure is depicted in Figure 12. The results demonstrated that the horizontal PCM could be located not only inside but also in the middle of the serrated area. Abdulrahman et al.[83] performed a numerical simulation of the PCM melting process

Figure 12. Sawtooth plate heat storage structure.

Table 5. Research on HTF Pipeline Structure

Reference	PCM	Type of Research	Heat exchanger type	Key structures/variables	Examining parameters	Enhance efficiency
Shahsava[63]	RT35	Numerical	Double tube type	HTF flow rate, inlet temperature	Melting time	20%
				Ripple and amplitude of channels	Solidification time	25%
Shahsava[64]	RT35	Numerical	Three-tube type	Ripple and amplitude of channels	Melting time	29%
Keshteli[65]	RT82	Numerical	Three-tube type	Bellows geometry	Solidification time	11%
				Nanoparticle volume fraction		
Mazhar[66]	\	Experimental	Other styles	Ripple and amplitude of channels	Melting time	10%
		Numerical			Solidification time	
Fallah[67]	Lauric acid	Numerical	Spiral tube type	Multilobe interface twist tube	Melting time	15.3%
Saydam[68]	Paraffin wax	Experimental	Spiral tube type	HTF temperature, flow rate, flow direction	Melting time	35%
Ardahaie[72]	$NaNO_3$	Experimental	Spiral tube type	Flat Spiral Coil	Melting time	21%
		Numerical		System tilt angle		
				HTF flow rate, inlet temperature		
Joybari[73]	RT60	Experimental	Multitube type	Multitube geometric arrangement	Melting time	73%
				HTF Flow Rate	Solidification time	
Kirincic[74]	RT25	Experimental	Multitube type	Separate fins for runners	Melting time	52%
				HTF flow rate, temperature		
Esapou[47]	RT35	Numerical	Three-tube type	Increase the number of inner tubes	Melting time	41%
				Inner tube arrangement	Solidification time	23%
Riahi[77]	\	Numerical	Three-tube type	Simplify design and materials	Melting time	18%

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Table 6. Studies on Other Runner Structures

Reference	PCM Types	Type of Research	Heat exchanger type	Key structures/variables	Examining parameters	Enhance efficiency
Santos[79]	\	Experimental	Board type	Panel surface shape	Melting time	50%
		Numerical		Steel plate thickness		
				HTF Temperature		
Gürel[80]	RT-35	Numerical	Board type	Flat geometry	Melting time	63%
				HTF Temperature		
Talebizadehsardari[81]	36 °C phase change temperature	Numerical	Plate fin type	Change the angle of the serration	Melting time	32.6%
Mahani[82]	RT-35	Numerical	Plate fin type	HTF Temperature	Melting time	8%
				Serrated plates		
Abdulrahman[83]	Paraffin wax	Numerical	Plate fin type	Triangle Channel	Melting time	21%
				HTF Flow Rate		
Li[84]	\	Experimental	Micro Heat Pipe	Adopt flat micro heat pipe array	Melting time	40%

in a plate−fin heat exchanger utilizing triangular inner wall paraffin. The results indicated that increasing the air Reynolds number enhanced the heat exchange efficiency.

In recent years, the microheat pipe heat exchange method has been incorporated into the heat exchange structure of phase change heat storage devices. Li[84] developed an experimental system to evaluate the performance of a PCM heat storage unit utilizing a flat plate microheat pipe array as the core heat exchange element, with lauric acid as the PCM. The findings demonstrated that the flat plate heat pipe array exhibited uniform temperature distribution during heat storage and release, and the heat storage unit exhibited efficient and stable performance.

In conclusion, Table 6 provides a summary of recent articles that modified the flow channel structure of the heat exchange medium. Flow channel configurations such as plate type, plate fin type, and micro heat pipe resemble the pipeline heat exchange method but often yield superior outcomes.

4. CONCLUSION

This review provides a comprehensive summary of two key aspects: enhanced heat transfer through the internal structure and enhanced heat transfer through the flow channels of the heat exchange medium. It presents an overview of various measures for enhancing heat transfer in different types of phase change heat storage devices, examines the influence of structural parameters on heat transfer, and presents the following conclusions:

(1) The primary objective of fin design is to address the issue of melting hysteresis in specific regions using various structures and arrangements, including nonuniform fins, tree-shaped fins, and others. This approach aims to effectively minimize the overall equipment melting time.

(2) CLHS can maintain the temperature difference between PCM and HTF within a specified range by carefully selecting and arranging the PCM. However, it is common practice to limit the number of PCM stages to 3−6 in order to prevent excessive complexity within the system.

(3) Utilizing porous media encapsulation can substantially enhance the internal heat transfer performance of PCM. However, this approach is associated with drawbacks such as increased weight and a high volume fraction of porous materials. Therefore, it is preferable to employ high-porosity porous media encapsulation in conjunction with nanoparticles, fins, and other heat transfer enhancement structures characterized by a low volume fraction. This combination aims to minimize the melting time of the system while ensuring efficient heat storage. Simultaneously, it is crucial to maximize the proportion of PCM to facilitate natural convection during the melting process.

(4) The utilization of a multitube design allows for an increased heat transfer area between the working fluid and the PCM heat storage device without altering the flow rate of the heat medium, thereby improving the heat transfer efficiency. Furthermore, the incorporation of built-in fins in the multitube structure enhances both heat conduction and convection heat transfer in the heat exchanger.

(5) In heat exchanger structures such as plate type and plate-fin type, it is important to avoid excessive thickness of the PCM-filled plates. Additionally, the utilization of serrated and corrugated channels can further enhance the heat exchange area between the plates.

5. FUTURE RESEARCH DIRECTIONS

(1) The experiments conducted in this review focus on designing various fin configurations tailored to specific heat exchanger types and operating conditions. The study examines the number, thickness, size, spacing, helix angle, and other relevant parameters of specific fin types. In future research, a comprehensive comparison can be made between various configurations of ring ribs and straight ribs based on a unified standard. Furthermore, the optimal fin configuration can be determined through dimensionless analysis or by combining the advantages of both configurations, fostering continuous innovation.

(2) In addition to verifying the thermal storage efficiency of the phase change thermal storage system under varying inclination angles, future research can explore the impact of altering the magnetic field, velocity field, and microgravity on the PCM melting process. It is essential to consider the relationship between the energy consumption associated with modifications in the physical field and the enhancement of thermal storage efficiency during these experiments.

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(3) Extensive research has been conducted on integrating CLHS with various conventional heat transfer enhancement techniques. However, there has been comparatively less focus on the targeted optimization of these structures specifically for CLHS. Thus, there remains ample potential to further explore and exploit the performance of CLHS.

The integration of fins, packaging method, flow channel shape, flow channel arrangement, and numerical simulation verification through software represents a significant trend in the design and development of heat exchange structures for future heat storage equipment. Naturally, the design of the heat exchange structure for heat storage devices must prioritize practicality and economy while striving to enhance the system performance within the constraints of manufacturing cost.

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Author Contributions

Weijian Zhang reviewed and compiled the relevant literature to write the review. Liang et al. ensured that this review was accurately described and agreed by all authors. Dali Ding, Rundong Zhang, Jianrui Bai, and Qi Du commented on and critically reviewed the review.

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