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Review

A Review on Heat Transfer Enhancement of Phase Change Materials Using Fin Tubes

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Abstract: Latent heat thermal energy storage (LHTES) has received more and more attention in the thermal energy storage field due to the large heat storage density and nearly constant temperature during phase change process. However, the low thermal conductivity of phase change material (PCM) leads to poor performance of the LHTES system. In this paper, the research about heat transfer enhancement of PCM using fin tubes is summarized. Different kinds of fins, such as rectangular fin, annular fin, spiral fin, etc., are discussed and compared based on the shape of the fins. It is found that the longitudinal rectangular fins have excellent heat transfer performance and are easy to manufacture. The effect of fins on heat transfer enhancement is closely related to the number of fins and its geometric parameters.

Keywords: thermal energy storage; phase change material; fin structure; melting and solidification

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1. Introduction

In recent years, economic development and population growth have triggered the rapid growth of world energy demand. Due to the depletion of fossil fuels and the rise in greenhouse gas emissions, the efficient use of renewable energy has attracted extensive attention. However, due to intermittency and instability, it is necessary to use energy storage to make up for the imbalance between energy supply and demand. Heat storage is one of the most important technologies in energy storage.

There are three types of heat storage methods: sensible heat thermal energy storage (SHTES); latent heat thermal energy storage (LHTES); and thermochemical energy storage (TCHS). SHTES realizes heat storage through temperature change without phase change in the heat storage materials. LHTES is also called phase change heat storage, which uses the latent heat absorbed or released by materials during phase change. TCHS utilizes reversible chemical reaction to achieve the heat storage and release. The mechanism of SHTES is simple and the technology is mature, but the temperature is unstable, and the heat release rate is uneven during the discharging process. TCHS has the characteristics of the highest heat storage density, but it is still in the initial research stage due to its complex reaction and high cost. Among the three methods, LHTES has attracted extensive attention due to the high energy storage density and nearly constant temperature during the phase-change process [1].

Solid–liquid phase change has higher latent heat compared with solid–solid phase change, and a smaller volume change compared with gas–liquid or gas–solid phase change, so the commonly used material in LHTES is solid–liquid phase change material (PCM).

PCMs are usually filled in various heat storage devices, where other heat transfer fluids (HTF), such as water and air, are needed to achieve heat transfer.

The low thermal conductivity of most PCMs leads to the poor performance of LHTES systems. There are many methods proposed from the aspects of materials, devices and systems to enhance the heat transfer of PCM; for example, adding nanoparticles or porous media with high thermal conductivity in PCM, preparing microencapsulation PCM, optimizing the structures of heat storage device, etc. There are different kinds of heat transfer devices for LHTES systems, including flat plate type, shell and tube type, packed bed, etc., as shown in Figure 1 [2]. The flat plate heat storage device is a flat cuboid, in which heat transfer pipes can be arranged and the PCMs are filled outside the pipes. The packed bed is equipped with large amounts of the heat storage unit filled with PCMs. The HTF flows through the pores between the heat storage unit to store and release heat. The shell and tube heat storage device can be divided into a single-pipe structure, multi-pipe structure and triplex tube structure according to the number and layout of the pipes. According to the position of HTF and PCM, it can be divided into two types: one is that the PCM is filed in the shell side of the device and the HTF flows through the tube to exchange heat with the PCM. Another one is that the HTF flows through the shell side and the PCM is filled in the tube side. At present, shell and tube type is one of the most commonly used devices in LHTES applications.

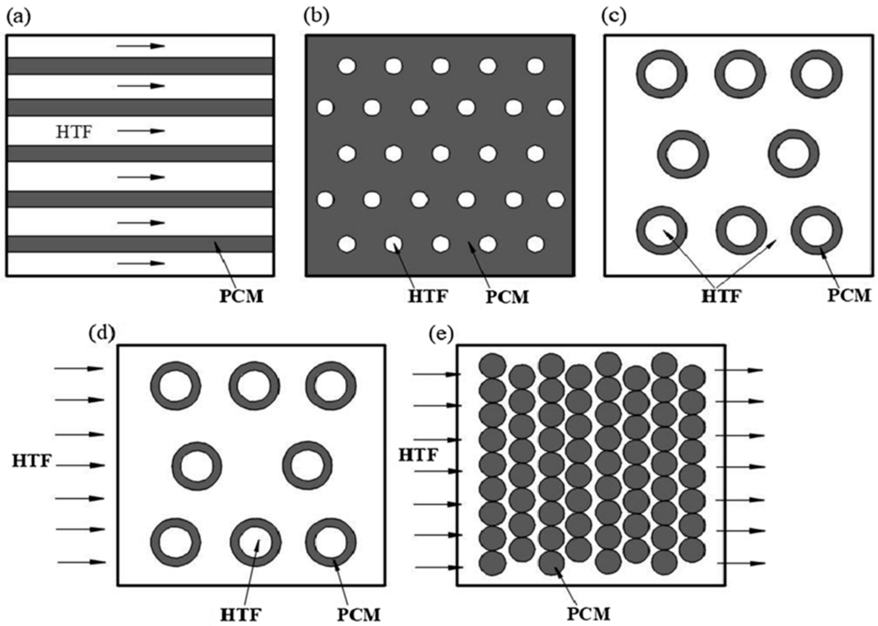


Figure 1. Different types of LHTES devices. (**a**) Flat plate; (**b**) Shell and tube—internal flow; (**c**) Shell and tube—parallel flow; (**d**) Shell and tube—cross flow; (**e**) packed bed. (Permission to reproduce from Ref. [2]).

One of the most efficient methods to enhance the heat transfer performance of the LHTES devices is using the fin structure to extend the heat transfer area. The fin structure is usually applied in shell and tube type LHTES, where the PCM is filled in the shell side. The HTF with high or low temperature flows through the tube to supply heat to, or obtained heat from, the PCM. Water is the most commonly used HTF in the low temperature field, and oil or air is usually used in medium and high temperature fields. The PCM could be considered as stationary, although there is weak natural convection when the PCM is in liquid state. The largest thermal resistance during the heat transfer from HTF to PCM appears at the segment from the tube to PCM due to the low thermal conductivity of PCM. Therefore, the fin structure is usually arranged at the PCM side based on the heat transfer enhancement principle that reduces the largest thermal resistance during the heat transfer process.

There has been much research reported about the effects of fin structures and parameters on the heat transfer performance of the shell and tube type LHTES devices. Many different shapes of fins and fin design methods are proposed, such as rectangular fins [3], annular fins [4], spiral fins [5], plate fins [6] and dendritic fins [7], as shown in Figure 2. Some reviews have summarized a part of the research about the heat transfer enhancement of PCM using fin tubes [2,8–10]. However, these reviews mainly focused on different methods including composite PCM, microencapsulated PCM, etc., for improving the heat transfer performance, or on different LHTES devices. There is a lack of comprehensive review on fin structures in the field of heat transfer enhancement of PCM. In this paper, the research on different fin shapes and their effects on the LHTES devices in recent years is summarized, and the classification is according to the fin shape. It is hoped that this paper is helpful to explain the heat transfer enhancement of fin structures in PCM and provide reference for the design of LHTES devices.

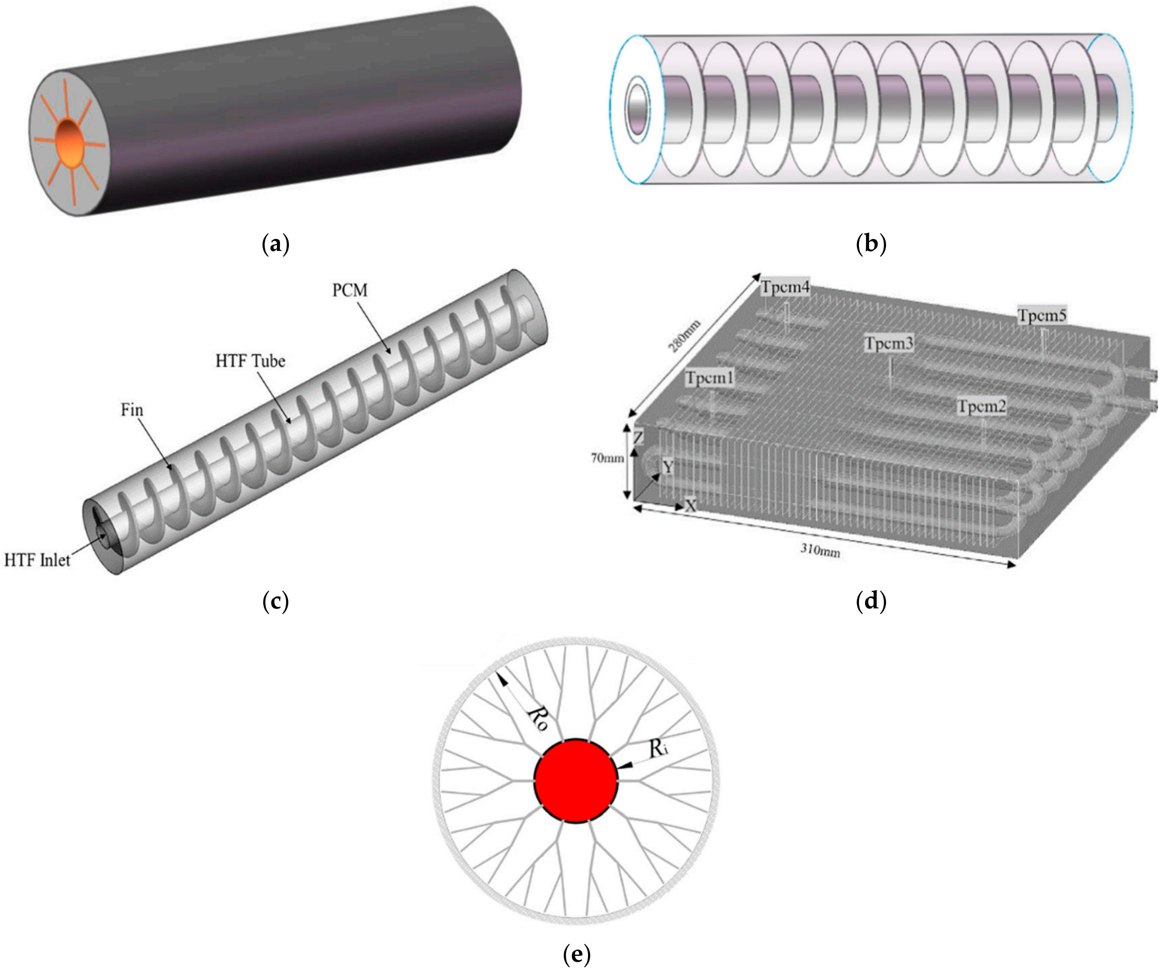


Figure 2. Different shapes of fin structure in LHTES devices. (**a**) Rectangular fins [3]; (**b**) Annular fins [4]; (**c**) Spiral fins [5]; (**d**) Plate fins [6]; (**e**) Dendritic fins [7]. (Permission to reproduce from Refs. [2–7]).

2. Heat Transfer Enhancement of Fin Structure in LHTES Device

The shell and tube type LHTES devices can be roughly divided into single-tube structures, multi-tube structures and triplex tube structures. Various research reports will be introduced below based on the application of different fin shapes in shell and tube heat storage units. Fins are usually arranged at the side with poor heat transfer performance in the LHTES system, that is, at the side filled with PCM, to improve the heat storage and release performance of the system.

There are some different indicators used to evaluate the performance of the LHTES devices, such as charging/discharging time, rate (or power), efficiency, exergy efficiency, or the same indicators for total process combined with heat storage and release. The charging/discharging time represents the duration from the initial state to the time that the lowest or average temperature of PCM achieves a certain temperature higher/lower than the phase change temperature. The charging/discharging rate represents the ratio of stored/released energy to the charging/discharging time. Some investigations used charging/discharging time or temperature evolution to qualitatively reflect the charging/discharging rate. The charging/discharging efficiency or exergy usually represent the ratio of energy or exergy stored/released in/from the PCM to that supplied/obtained by the HTF. The most common indicator applied to evaluate the enhancement performance of fin tubes for the heat transfer of PCM in LHTES is the charging/discharging time, which could intuitively reflect the heat transfer performance at the same working condition.

2.1. Rectangular Fin

Longitudinal rectangular fins are usually applied in industrial production due to the advantages of simple structure and ease of manufacture [11]. The investigations about the rectangular fin in single-tube heat storage units mainly focus on the effects of fin length, thickness, location and other factors on the performance of the LHTES system and the optimization of fin parameters. Nie et al. [12], Mahood et al. [13], Li et al. [14] and Soltani et al. [15] investigated the influences of the arrangement, number and length of rectangular fins on the performance of horizontal heat storage units with a single tube. Increasing the number and length of fins can accelerate the heat storage and release rate and increasing the fin length could shorten the melting time of PCM. The natural convection of liquid PCM would lead to the inhomogeneous heat transfer intensity in the upper and lower parts. Therefore, the melting time could be reduced by thickening the bottom fins and making the top fins thinner. In addition, extending the bottom fins could also enhance the heat transfer performance in the lower half area.

The fin angle also affects the heat transfer performance of the heat storage unit. Kumar and Verma [16] found that the fin angle at 60° showed a better effect than that at 120° and 180° on the heat transfer enhancement. Kazemi et al. [17] proved that the melting rate was the fastest at the included angle of 60° when three fins were arranged in the upper part of the device. The best effect appeared at the included angle of 45° when two fins were arranged in the lower part. Khan and Khan [18] indicated that the melting rate was the highest when the included angle is 30°, where the included angle between the fin and horizontal direction was used to represent the variation in fin direction.

There are also some studies about the effect of fin position on the heat transfer performance of the heat storage unit. Deng et al. [19,20] found that the best enhancing effect appeared when two fins are symmetrically arranged in the lower part of the device and the fin angle was 120°, which could reduce about 66.7% melting time compared with that at a 30° fin angle. Distributing fins in the lower part made the melting of PCM more uniform when the number of fins was less than or equal to 6. In addition, when the number of fins was more than 6, the melting time is shortest at uniform fin distribution. Yu et al. [21] designed rectangular fins with gradient thickness and gradient fin angle. The melting time of PCM with the designed fin structure was reduced about 30.5% compared with uniform fins. Tang et al. [3] designed different arrangement structures with non-uniform fins. The results showed that the melting time was reduced by 83.9% compared with the structure without fins, when the angle of fins distributed at the lower part was 25° and the length was 40 mm.

In addition, Mahdi et al. [22] found that the melting rate of PCM without fins in horizontal heat storage units was usually higher than that in vertical units due to the natural convection effect. However, the rectangular fins played an inhibitory effect on the natural convection, leading to the similar heat transfer performance between horizontal and vertical heat storage units. Kumar and Verma [16], and Khan et al. [23] studied the enhancing effect of tune eccentricity on the heat transfer, where the eccentricity was the ratio of the center distance between the inner tube and the shell to the shell radius. It was found that eccentric arrangement could enhance the natural convection and shorten the melting time. Soltani et al. [15] found that the melting and solidification time could be reduced through the rotation of the device, and the effect was better when the rotation speed was high.

For the LHTES device with multi-tube, Khan and Khan [24] experimentally investigated the rectangular fins on vertically coils in shell and tube heat storage units. The results show that the heat conduction was the main heat transfer mode during the discharging process, and the heat transfer rate increased due to the coil and fin structure. Nóbrega et al. [25] studied the influence of fins on the solidification process of water. The results showed that the increase in fin number and fin length could reduce the solidification time, but also reduce the heat storage capacity. There was an optimal fin length, beyond which the improvement in heat transfer could be ignored because the temperature gradient between the fin end and surrounding PCM was significantly small. Pan et al. [26] proposed a layered thermal resistance model based on the two-dimensional cylindrical geometry structure to describe the nonlinear transient solidification process in single-tube and multi-tube heat storage units using the analytical equations. The costs were optimized under operation requirement constraints, and the results showed that the thinner fins reduced the cost of the heat storage unit. Dai et al. [27] studied the effects of fin structure in horizontal heat storage units. A single fin at the bottom and double fins arranged along a vertical direction displayed the best heat transfer performance. The single long fin showed better heat transfer performance than two short fins. Qaiser et al. [28] investigated the influence of the shapes of multi-tube and shell on the heat transfer of the horizontal LHTES heat storage unit. Three rectangular fins were uniformly arranged in a Y-shape on each heat transfer tube. It was found that the vertical double fins and V-shaped three-tube structures showed better heat transfer performance that the single-tube structure. The elliptical shell and triangular shell could also enhance the heat transfer. Kirincic et al. [29,30] studied the effect of rectangular fins on the performance of a vertical heat storage unit with multi-tube structure. The melting and solidification times were reduced by about 52% and 43%, respectively, compared with those of the heat storage unit without a fin. They indicated that the actual influence of rectangular fins on the natural convection was significantly small, and the volume reduction in PCMs caused by adding fins could be ignored.

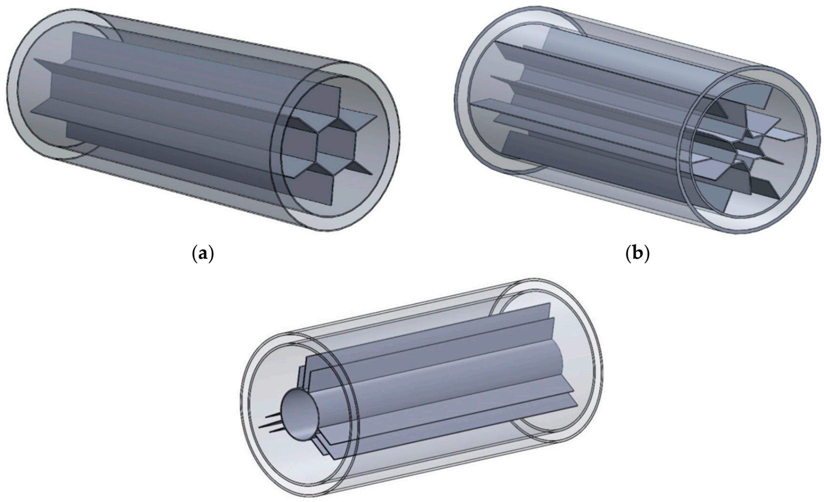
The rectangular fins are also applied in heat storage units with a triplex tube structure, where the fin is added to the middle layer of the triplex tube. Eslamnezhad and Rahimi [31], Mahdi and Nsofor [32], Cao et al. [33] and Zarei et al. [34] studied the optimal design of rectangular fins in the triplex tube heat storage unit. Increasing the number of fins could improve the melting rate, but there is the best number of fins for the heat transfer enhancement. Increasing the fin length or decreasing the fin thickness in a certain range could reduce the charging and discharging time. Suitable fin deflection angle or eccentric arrangement of the inner tube could also reduce the melting time of PCM. Joybari et al. [35] compared the effect of different arrangements of rectangular fins in triplex tube heat storage units. It was found that adding fins in the upper part of outer wall or in the lower part of the inner wall of the middle layer was helpful for the melting of PCM.

It has been proven that adding rectangular fins could improve the melting and solidification rate of PCMs. The existence of rectangular fins would affect the development of natural convection, but it can enhance heat conduction at the same time. Increasing the length of rectangular fins could enhance heat transfer. In structure, non-uniform distribution and eccentric placement of pipes could increase the melting rate of PCM. Table 1 summarized the applications of rectangular fins in LHTES units.

Table 1. Application of rectangular fins in LHTES units.

References	Year	Pipe Types	Exp/ Num	Melting/ Solidification	PCM	Findings Description
Nie et al. [12]	2020	Single-tube	N	M/S	Lauric acid	Increasing the fin number and length accelerated the heat storage/release rate. The total heat storage and release time reduced about 67.9% when fin number increased from 2 to 10.
Mahood et al. [13]	2020	Single-tube	N	M	Paraffin (type RT-50)	The melting time was apparently reduced through increasing fin length. The best performance appeared when all fins arranged in the lower part of heat storage unit and the angle between fins was small.
Li et al. [14]	2021	Single-tube	N	M	Paraffin wax (RT52)	Both thickening/extending the bottom fins and thinning the top fins could reduce the melting time of PCM. The optimized fin structure reduced about 54.1% melting time.
Soltani et al. [15]	2021	Single-tube	N	M/S	N -eicosane	The rotation of the device enhanced the natural convection, resulting in the reduction in melting and solidification times. The performance was better at higher rotating speed.
Kumar and Verma [16]	2020	Single-tube	E/N	M	Lauric acid	Fin structure with lower fin angle of 60° showed better performance than that at fin angle of 120° and 180°. The heat storage rate of eccentric structure was 18.7% higher than that of concentric structure.
Kazemi et al. [17]	2018	Single-tube	N	M	RT 35	The melting rate was the fastest when three fins were arranged at 60° included angle in the upper part. Best performance appeared at the included angle of 45° when two fins were arranged in the lower part.
Khan and Khan [18]	2020	Single-tube	N	M	Stearic acid	The melting rate was the highest when the included angle between the fin and the horizontal direction was 30°. Increasing the ratio of fin length to thickness improved the melting rate.
Deng et al. [19,20]	2019	Single-tube	N	M	Lauric acid	The fins arranged in the lower part when the fin number was less than or equal to 6, or uniformly distributed when fin number was greater than 6, could improve the melting of PCM.
Yu et al. [21]	2020	Single-tube	N	M	Paraffin wax RT58	The melting time was reduced about 30.5% using gradient fin thickness or gradient fin angle.
Tang et al. [3]	2021	Single-tube	N	M	Paraffin RT50	Concentrating fins in the lower area could reduce the melting time by about 83.9%.
Mahdi et al. [22]	2019	Single-tube	N	M	Paraffin wax	The melting time decreased with increasing the HTF temperature. The flow rate showed slight effect.
Khan et al. [23]	2021	Single-tube	N	M	Stearic acid	Eccentric pipe arrangement could reduce the melting time through enhancing natural convection.
Khan and Khan [24]	2017	Coil pipe	E	S	Paraffin (RT44HC)	Coil and rectangular fin structure enhanced the heat transfer. Heat conduction was the dominate heat transfer mode during heat release process.
Nóbrega et al. [25]	2020	Multi-tube	E/N	S	Water	Increasing fin number and length reduced the solidification time and heat storage capacity.
Pan et al. [26]	2017	Multi-tube	N	S	Not given	The estimated system cost using carbon steel was slightly lower than that using Al 6061.
Dai et al. [27]	2020	Multi-tube	N	M	Water	The fin structures with bottom single fin or vertical double fins had the best heat transfer performance. The fin structure with a single long fin was better than that with two short fins.
Qaiser et al. [28]	2021	Multi-tube	N	M/S	Stearic acid	The vertical double fins and V-shaped three-tube structures showed better heat transfer performance that the single-tube structure.
Kirincic et al. [29,30]	2021	Multi-tube	N	M/S	Paraffin RT 25	The melting and solidification time reduced by about 52% and 44%, respectively, using rectangular fins instead of finless structure.
Eslamnezhad and Rahimi [31]	2017	Triplex tube	N	M	RT82	The melting rate was improved through adjusting the number and deflection angle of fins or arranging the inner tube eccentrically.
Mahdi and Nsofor [32]	2017	Triplex tube	N	M	RT82	Rectangular fin structure showed better performance than nanoparticles. Increasing fin length or decreasing fin thickness were helpful to enhance the heat transfer.
Cao et al. [33]	2018	Triplex tube	N	M	Lauric acid	Increasing fin number improved melting rate, which was more apparent at lower wall temperature.
Zarei et al. [34]	2020	Triplex tube	N	S	RT82	The solidification process was accelerated through increasing fin length or decreasing fin thickness in a certain range. The arrangement of fins on inner and outer tube had a slight effect.
Joybari et al. [35]	2017	Triplex tube	N	M/S	RT31	Adding fins to the upper part of outer wall or lower part of inner wall of the middle layer could improve the melting rate of PCM.

Many researchers have made innovations based on the above ordinary longitudinal rectangular fins, for example, combining multiple fins into a new structure, creating holes on the fins, attaching metal foam, etc. Zhai et al. [36] proposed a single-tube LHTES unit, dividing the interior into 20 connected cavities through 4 annular fins and 4 rectangular fins. The experimental results showed that the solidification time reduced about 71.2% compared with that of the structure without fins. The optimized structure could further reduce 26.3% solidification time compared with the experimental results. Hosseinzadeh et al. [37,38] designed hexagonal-shaped and star-shaped triplex tube LHTES units, as shown in Figure 3a,b. The solidification rate of PCM in a hexagonal-shaped heat storage unit is 8% faster when using fins compared with that without fins. For the star-shaped tube, the solidification rate could be increased by 9% when rectangular fins were added to the inner and outer walls of the middle layer of triplex tube. Both studies indicated that the effect of adding fins was better than that of adding nanoparticles. Thereafter, Hosseinzadeh et al. [39] proposed a triplets fins structure shown in Figure 3c. It was found that this structure could enhance heat transfer performance during the solidification process, and the use of this structure together with nanoparticles further enhanced heat transfer. Kok [40] proposed a new structure with local fins arranged at the end of the tube. They indicated that the melting time reduced by about 63% when using the local rectangular fins instead the structure without fins. Gürtürk and Kok [41] designed four kinds of local fins and found that the melting time of PCM in the structure with local rectangular fins at both ends of the tube was similar to that with the whole rectangular fin. In addition, the effect of fins during the solidification process of PCM is weaker than that during the melting process. Ding and Liu [42] studied perforated fins and slotted fins based on rectangular fins. The use of perforated fins and slotted fins played a role in promoting natural convection, improving the melting rate compared with common rectangular fins. The performance of slotted fins was better than that of perforated fins, because they can reduce the plugging effect while retaining a large heat transfer area. Tokas et al. [43] discussed the influences of heat transfer coefficient, fin thickness, fin interval, fin material and other parameters on the efficiency and effectiveness of grid fins. There was an optimal dimensionless fin thickness for any dimensionless fin length. Mahdi et al. [44] proposed the method of adding metal foam strips onto rectangular fins. They found that the addition of metal foam strips inhibited natural convection during the melting process, but promoted heat conduction to a greater extent, which was helpful to enhance heat transfer. Malik et al. [45] numerically investigated the performance of shell and tube LHTES systems with fin tubes for waste heat recovery system. The LHTES systems using HITEC industrial salt as PCM could dampen the source temperature fluctuations by more than 80%.



(**a**) (**b**) (**c**)

Figure 3. Different triplex tube heat storage units. (**a**) Hexagonal-shaped triplex tube [37]; (**b**) Star-shaped triplex tube [38]; (**c**) Triplets fins triplex tube [39]. (Permission to reproduce from Refs. [37–39]).

2.2. Annular Fin

Annular fins are usually applied in cylindrical LHTES systems. Yang et al. [46], Cheng et al. [47], Shahsavar et al. [48] and Bhagwat et al. [49] verified the effect of annular fins on the heat transfer enhancement, which could reduce the melting time of PCM compared with the structure without fins. However, excessive fins would affect the generation and development of natural convection. The annular fins show more obvious effects on melting process than on solidification process. Shahsavar et al. [48], Ismail et al. [50] and dos Santos et al. [51] investigated the influences of the number, diameter and thickness of annular fins on the performance of LHTES units. Increasing the fin diameter could reduce the melting/solidification times of PCM. The solidification process could be accelerated when increasing the number of fins, whereas the fin thickness has relatively small effect on the solidification time.

Some scholars have studied the influence of annular fin angle shown in Figure 4 on the melting and solidification process of PCMs. Guo et al. [52] found that the melting of PCM near the vertical direction of annular fin was promoted when the fin angle was 5°, 10° and 15°, but that near the radial direction was weakened. Excessive fin angle would slow down the melting process. Parsazadeh and Duan [53] indicated that the fin angle and the concentration of nanoparticles greatly affected the melting of PCMs. Positive fin angle is conducive to the melting, and the optimal fin angle was 35°. There was an area unfavorable for heat transfer below the fin at negative fin angle. Mahmoud et al. [54] studied the influence of fin angle on the melting process when the annular fins were respectively arranged on the pipe walls at both sides of the middle layer of triplex tube heat storage unit. The effect of annular fin on the heat transfer enhancement was the best when the fin angle was negative on the inner wall and positive on the outer wall, which was better than that with the annular fins on both sides are in the same direction.

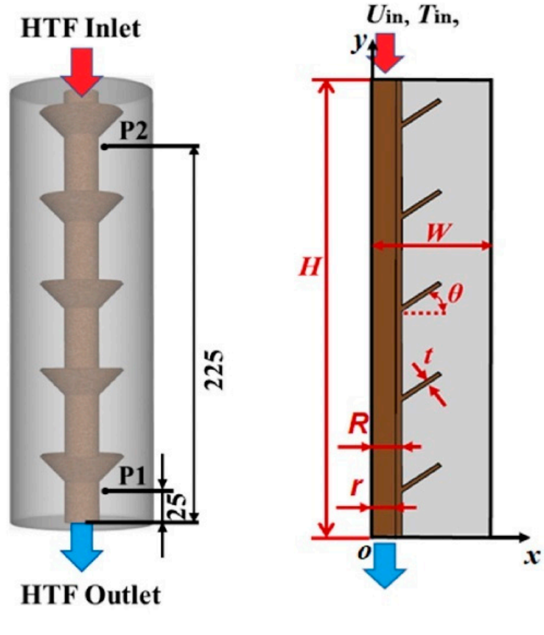


Figure 4. LHTES unit with annular fins [52]. (Permission to reproduce from Ref. [52]).

Perforating on annular fins could enhance the natural convection. Karami and Kamkari [55] compared finless, holeless annular fins and perforated annular fins LHTES units. The average Nusselt number of perforated fin structure was about 30% higher than that of a holeless fin structure, and the total melting time was reduced about 7%. Li et al. [56] considered that increasing the diameter of the hole on the annular fin or decreasing the distance from the hole to the fin root would enhance the natural convection and weaken the heat conduction. The melting time could be reduced about 5.49% by selecting the optimum hole diameter and position.

Pu et al. [4] studied the influence of fin length and interval in the vertical LHTES with four kinds of fin arrangement. The results showed that the temperature distribution during the melting process was more uniform when the fin interval decreased from top to bottom, and the melting rate was the highest among the four kinds of fin arrangements. Ghalambaz et al. [57,58] compared different non-uniform arrangements of annular fins, as shown in Figure 5. The optimal scheme, in which large fins were placed at the bottom and small fins were placed at the top, is shown in the rightmost structure of Figure 5. The fins at the bottom were beneficial to heat conduction, leading to the rapid melt of PCM. Decreasing the diameter of the top fin could reduce the inhibition of the fin on natural convection. Tiari et al. [59] found that the optimal arrangement during the heat storage process was that the diameter of 20 fins increased gradually from top to bottom., The best configuration for the heat release process was that the 20 fins had the same diameter, and the total heat storage/release time of the device was the shortest. Kalapala and Devanuri [60] studied the performances of LHTES units with annular fins at different inclination angles. It was indicated that the vertical heat storage unit showed better performance in melting time and average Nusselt number.

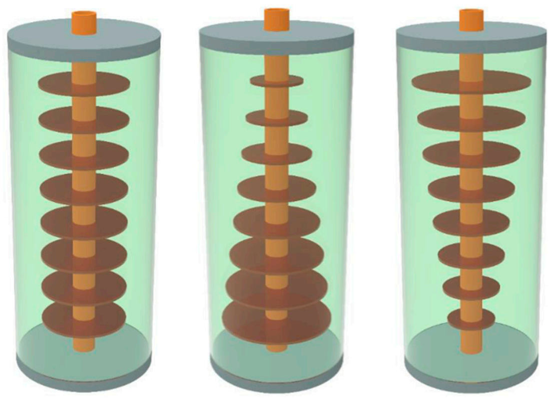


Figure 5. Different arrangements of annular fins [57]. (Permission to reproduce from Ref. [57]).

From the above, the research on annular fins mainly focuses on the size, number, position and structure of fins. Increasing the fin diameter, fin number, perforating the annular fin, designing non-uniform fin diameter and interval could enhance the heat transfer of heat storage unit. The applications of annular fins in LHTES units are summarized in Table 2.

Table 2. The applications of annular fins in LHTES units.

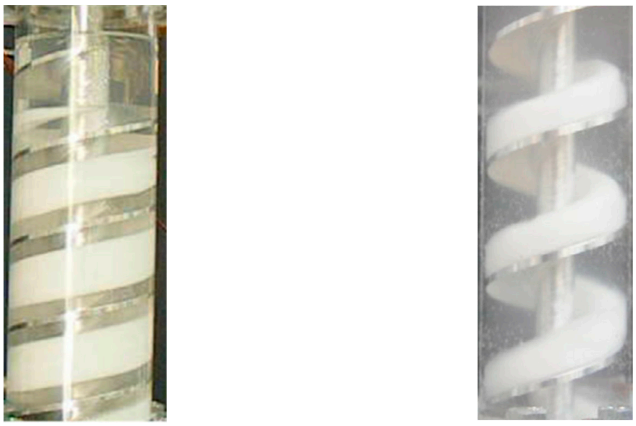
References	Year	Pipe Types	Exp/Num	Melting/Solidification	PCM	Findings Description
Yang et al. [46]	2017	Single-tube	N	M	Paraffin RT35	The melting time reduced about 65% using annular fins, but excessive fins affected the natural convection.
Cheng et al. [47]	2018	Single-tube	E	M	Paraffin wax	Annular fins improved the heat transfer performance and accelerated the melting process of PCM compared with finless structure.
Shahsavar et al. [48]	2020	Single-tube	N	M/S	Paraffin RT35	Annular fins obviously reduced the melting time, but showed slight effect on the solidification of PCM. Increasing the fin diameter could reduce the melting time.
Bhagwat et al. [49]	2021	Single-tube	E	M/S	Paraffin wax	The average heat storage/release rate was improved about 44.7% and 32.7, respectively, using annular fins instead of finless structure.
Ismail et al. [50]	2001	Single-tube	E/N	S	Paraffin 130/135 Type 1	The influence of fin thickness on solidification time was relatively small, and the increase in fin diameter and number reduced the complete solidification time.
dos Santos et al. [51]	2020	Single-tube	E/N	S	Water	Fins with large diameter could reduce complete solidification time.
Guo et al. [52]	2022	Single-tube	E/N	M	Paraffin wax	The smaller fin angle promoted the melting in the vertical direction and weakened the melting in the radial direction. Excessive fin angle slowed down the melting.

Table 2. *Cont.*

References	Year	Pipe Types	Exp/Num	Melting/Solidification	PCM	Findings Description
Parsazadeh and Duan [53]	2018	Single-tube	N	M	Paraffin wax	Fin angle greatly affected the melting of PCM, while the fin interval had slight effect.
Mahmoud et al. [54]	2021	Triplex tube	N	M	Paraffin RT35	The effect of annular fin on the heat transfer enhancement was the best when the fin angle was negative on the inner wall and positive on the outer wall.
Karami and Kamkari [55]	2020	Single-tube	E	M	Lauric acid	Perforated annular fins reduced about 7% melting time compared with holeless fins.
Li et al. [56]	2021	Single-tube	N	M	Paraffin wax	Increasing the diameter of the hole on the annular fin resulted in the enhancement of natural convection and weakness of heat conduction. The maximum reduction in melting time was about 5.49%.
Pu et al. [4]	2020	Single-tube	N	M	Paraffin RT35	The decreasing of fin interval from top to bottom made the temperature distribution during the melting process more uniform and the melting rate was the highest, which reduced the melting time by 49.9%.
Ghalambaz et al. [57,58]	2021	Single-tube	N	M	Coconut oil	Fins at the bottom were conducive to heat conduction. Small fins at the top were beneficial to the natural convection.
Tiari et al. [59]	2021	Single-tube	N	M/S	Rubitherm RT55	The best arrangement was when the fin diameter increased gradually from top to bottom during the heat storage process. Whereas, the optimal configuration was all fins having the same diameter.
Kalapala and Devanuri [60]	2021	Single-tube	E/N	M	Lauric acid	The heat storage unit in the vertical direction performed better in terms of melting time and average Nusselt number.

2.3. Spiral Fin

The investigations on spiral fins mainly adopted the heat storage unit with single-tube structure. Rozenfeld et al. [61] experimentally studied the melting process of PCM in the LHTES system, as shown in Figure 6. When the shell was slightly heated, a thin liquid layer formed near the shell and the solid part moved downward to directly contact the spiral fins, which reduced the melting time by two thirds compared with that under the condition of the shell without heating. Large radial dimensions of shell and fins resulted in a long melting time from the numerical investigations. Increasing the fin thickness was positive to the melting of PCM. Mehta et al. [5,62] experimentally studied the performances of vertical LHTES devices with spiral fins. The melting and solidification time decreased about 41.48% and 22.16% compared with that of finless structures, respectively. They also discussed the influences of inclination angle on the heat storage device. Compared with the vertical device, the melting time could be reduced by about 40.97% and 34.1%, respectively, when the heat storage device was placed at a 45° angle or along the horizontal direction.



(**a**) (**b**)

Figure 6. Different working conditions of LHTES unit with spiral fins [61]. (**a**) Shell exposed to air; (**b**) Shell slightly heated. (Permission to reproduce from Ref. [61]).

Duan et al. [63] numerically compared the heat transfer enhancement of multiple parallel spiral fins and rectangular fins in the horizontal LHTES system, as shown in Figure 7. The melting and solidification rates of spiral fins with different spiral periods were all higher than those of rectangular fins with the same fin numbers, due to the larger heat transfer area. Increasing the fin number and spiral period could significantly increase the melting and solidification rates. Ghalambaz et al. [64,65] numerically investigated the single-tube and triplex tube LHTES units with twisted helical fins. In the single-tube heat storage unit, the heat storage time of PCM with two twisted spiral fins was reduced about 42% compared with that using rectangular fins. In the triplex tube heat storage unit, the melting time of 4 twisted spiral fins was shorter than that of 4 rectangular fins and finless structures. Sun et al. [66] further studied the solidification process of PCM in the same heat storage unit. The results showed that the solidification time of PCM with 4 twisted spiral fins was 12.7% shorter than that with 4 rectangular fins. Increasing the number of twisted spiral fins could improve both the heat storage and release rates.

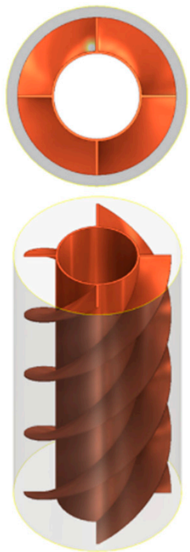


Figure 7. LHTES unit with multiple parallel spiral fins [63]. (Permission to reproduce from Ref. [63]).

2.4. Plate Fin

Plate fin is a common form in practical applications, which are mostly used in multi tube or coiled tube LHTES units. They generally have a large heat transfer area and are arranged compactly. Plate fins are usually perpendicular to the direction of the tube and pass through all pipes.

Pakalka et al. [67] experimentally compared the effects of two types of plate fin on the performance of coil LHTES devices. One with thin and more plate fins was connected through the expansion of copper tube, and the other one with thick and fewer fins was connected by welding. The melting and solidification rates of the former were slightly faster than those of the latter, and the former also had lower cost and smaller volume. Amagour et al. [68] experimentally studied the LHTES system using a compact plate fin tube heat exchanger. The performance of the system during the solidification process was better than that during the melting process, and the overall performance was better at small flow rate.

Amagour et al. [6] found that performance improvement was less obvious after the plate fin number increasing to a certain value through the numerical investigation, although increasing the fin number would accelerate the melting process. Increasing the fin thickness could also reduce the melting time. Mazhar et al. [69] numerically studied the heat transfer enhancement of plate fins. The results showed that the plate fins could improve the heat transfer performance compared with finless structures due to the enhanced heat conduction, although the natural convection was suppressed.

2.5. Topology Optimized Fin

Topology optimization is an optimization method of determining the optimal distribution of materials in a design domain [70]. This method does not need to initially provide a structure with approximate optimization design results, and the design will change dramatically during the optimization process [71]. Topology optimization is first used in the field of structure, and then gradually extends to heat transfer, fluid mechanics and other fields.

Pizzolato et al. [71–73] designed the optimal fin structure for the melting process of PCM by means of topology optimization. The natural convection played an important role in the optimization results, as shown in Figure 8. The fins at the bottom were elongated and there were only two short fins at the top when the natural convection was considered, leading to about 27% reduction in melting time. The optimization results without considering the natural convection were more conducive to heat conduction and more suitable for solidification process. Simplifying the optimization results into the combination of multiple rectangular fins, the heat transfer performance was still better than that of ordinary rectangular fins with the same volume fraction. They found that the 3D design could present fin features that were not obvious in 2D design, and the heat release time was reduced about 20%. Furthermore, the overall topology optimization of the multi-tube LHTES device shows better performance than the individual optimization of a single tube in the multi-tube device. Ge et al. [74] used 3D printing technology to manufacture the topology optimized fins [73]. They experimentally and numerically studied the solidification process of PCM in single-tube LHTES unit. The results showed that the fully solidification time of PCM could be significantly reduced by using topology optimized fins compared with rectangular fins. You et al. [75] compared the effect of topology optimized fins with longitudinal triangular fins and longitudinal rectangular fins in a horizontal single-tube heat storage unit. The topology of optimized fins showed the best heat transfer performance. Tian et al. [76] studied the bionic topology of optimized fins based on the optimization objective of minimizing the heat storage time. The optimized fins could reduce the melting time and solidification times about 93% and 80%, respectively, compared with the finless structure.

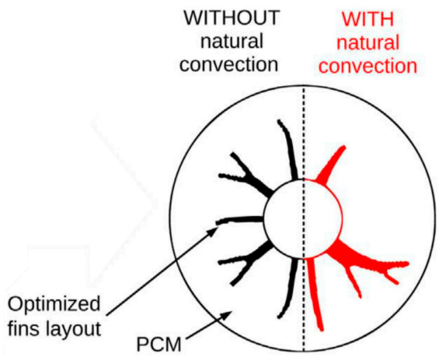


Figure 8. Topology optimized fins with and without natural convection [72]. (Permission to reproduce from Ref. [72]).

2.6. Dendritic Fin

Dendritic geometry is a high efficiency heat and mass transfer system, such as blood circulation system, river, branching structure of tree [77]. Dendritic fins can be regarded as the combination of several rectangular fins, they have been introduced into the LHTES device to improve the heat transfer performance in recent years. Some literature also named this structure as a tree-like fin or Y-shaped fin. In fact, topology optimized fin is one kind of dendritic fin. Due to the difference in optimization method and irregular shape, topology optimized fin is discussed individually above. Figure 9 is a schematic diagram of fourth-level dendritic fin, in which the important parameters related to the dendritic fin are shown, such as branch number, branch angle, branch length and width.

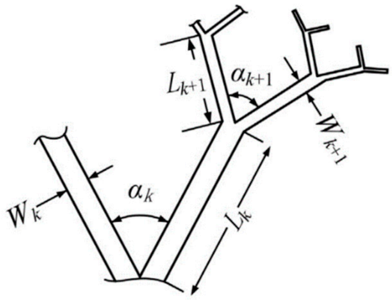


Figure 9. Four-level dendritic fins [77]. (Permission to reproduce from Ref. [77]).

Sciacovelli et al. [78] numerically studied the influence of single/double two-level dendritic fins (Figure 10) on the heat release process of vertical single-tube LHTES unit. Both the structures could promote the solidification of PCM, and the double bifurcation two-level dendritic fins improved the discharging efficiency about 24%. In addition, the optimal structure of dendritic fins depended on the operation time of the heat storage unit. The shorter the operation time, the greater the bifurcation angle of the dendritic fins. Zhao et al. [79] compared the influences of rectangular fins with unequal length, rectangular fins with unequal interval and two-level dendritic fins on the melting process of PCM in a horizontal heat storage unit. Due to the short length of two-level dendritic fins, there was little effect on the overall heat transfer performance. The rectangular fins with unequal length showed the best performance. Safari et al. [80,81] studied the influences of different dendritic structures and eccentric fin tube arrangement on the melting process of PCM in a single-tube LHTES unit. The experimental results showed that the addition of two-level dendritic fins and pipe eccentricity could increase the melting rate, and the performance of dendritic fins was better than that of rectangular fins. The numerical results showed that the diagonal cross arrangement was the best when the dimensionless length of two-level dendritic fins (the ratio of the fin length to the fin tube radius) was less than or equal to 0.63; whereas the uniform arrangement of fins in the lower part was the best when the dimensionless length increased to 0.89.

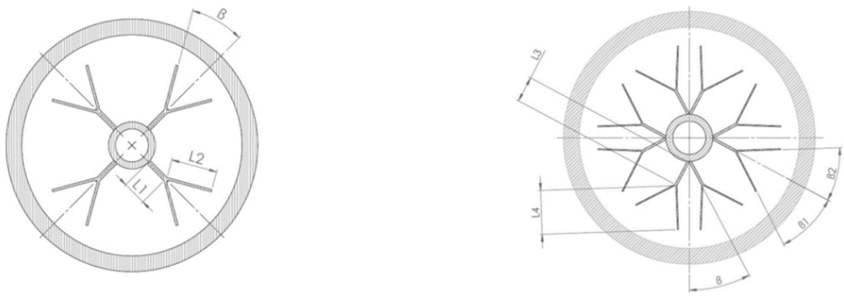


Figure 10. Different two-level dendritic fins [78]. (**a**) Single bifurcation; (**b**) Double bifurcation. (Permission to reproduce from Ref. [78]).

Some scholars investigated the effectiveness of dendritic fins through comparing with rectangular fins in a single-tube heat storage device at the same volume. Wu et al. [7], Zheng et al. [77] and Yu et al. [82] studied the melting and solidification processes of PCM in the heat storage unit, respectively. The solidification front of PCM with dendritic fins was more uniform compared with rectangular fins, which could significantly reduce the solidification time of PCM. Huang and Liu [83] found that the dendritic fins improved the temperature uniformity in the vertical LHTES device through 3D numerical simulation. The complete melting/solidification time was reduced by 34.5% and 49.2%, respectively, compared with rectangular fins. The time-averaged heat storage/release power was increased by 49.4% and 96.4%, respectively.

The optimization of dendritic fins in single-tube heat storage units is mainly related to the fin length, thickness, branch angle and position. Vogel and Johnson [84] studied the performance of a vertical LHTES system using dendritic fins. The results showed that the effect of natural convection increased with the increase in tube diameter and the decrease in fin volume fraction. The increase in fin branching was beneficial to the development of natural convection. Asgari et al. [85] found that thin fins or long fins could better improve the heat transfer rate when using dendritic fins. Hosseinzadeh et al. [86], Liu et al. [87], Peng et al. [88] and Huang et al. [89] studied the influence of branch angles. Increasing the branch angle of dendritic fins accelerated the melting and solidification processes of the LHTES system. The uniformly distributed dendritic fins showed better performance than rectangular fins with the same volume. The non-uniform dendritic fins were conducive to the melting process through enhancing both heat conduction and convection but showed slight effect on the solidification process. Huang et al. [90,91] found that the heat storage unit using dendritic fins was less affected by the inclination angle of the device compared with rectangular fins due to the enhancement on heat conduction and inhibition on natural convection. They proposed the graded fin based on the dendritic fin, which decreased the melting time compared with the ordinary dendritic fin through improving the heat conduction effect in the later melting stage.

Huang et al. [92] also investigated the multi-tube heat storage device with dendritic fins. The temperature uniformity of the device was improved through the dendritic fins. The inclination angle of the device showed more apparent effect on the melting process than that on solidification process. The melting time of PCM in a vertical device was reduced about 46.3% compared with that in horizontal devices. Song et al. [93] compared the performances of LHTES devices using dendritic fins and rectangular fins at the same volume. The melting time of PCM with dendritic fins reduced about 80.2% and 34.4% compared with finless and rectangular fins structures. Although the development of natural convection was suppressed during the melting process by the dendritic fins, the influence range of natural convection was expanded.

Alizadeh et al. [94] used the two-level dendritic fins and nanoparticles together to improve the performance of triplex tube heat storage unit. The solidification time could be reduced by decreasing the trunk length of the fin or increasing the branch length and angle. Hajizadeh et al. [95] numerically studied the effect of two types of dendritic fins (long fins placed at the top or the bottom) and nanoparticles in triplex tube LHTES system. The solidification rate of PCM with structure in which long fins were placed at the top was higher. Compared with the case without fins, the solidification time of the two arrangements was reduced by 64.5% and 70.06%, respectively. Li et al. [96] discussed the heat transfer enhancement of two-level dendritic fins together with nanoparticles on the triplex tube heat storage unit. It was indicated that adding fins on the inner and outer walls of the middle layer simultaneously could reduce the melting time of PCM. Longer fins were more conducive to the heat transfer enhancement. Zhang et al. [97] found that the melting and solidification times of PCM in triplex tube LHTES device reduced about 4.4% and 66.22, respectively, when using dendritic fins instead of rectangular fins. The optimal length ratio (the secondary level to the first level) was about 1.3 and the optimal thickness ration was 1. Hosseinzadeh et al. [98] investigated the influences of dendritic fins and nanoparticles on the solidification process of PCM in triplex tube LHTES unit. The solidification time reduced about 51.4% comparing dendritic fins structure with rectangular fins structure. Further reduction to 78% could be achieved through combing dendritic fins with nanoparticles.

There is another type of dendritic fin where parallel multi-level branch appeared on a long main branch. Deng et al. [99] designed dendritic fins simulating the shape of fern leaves. The average heat storage rate was improved 83.3% and the melting time was reduced 40.3% for the designed fins compared with rectangular fins. Research by ul Hasnain et al. [100,101] examined the combination effect of nanoparticles and three different fin structures (non-uniformly distributed rectangular fins, single-branched fins, double-branched fins). The melting time of PCM reduced about 22.9%, 35.4% and 45.9% for the three kinds of fins compared with uniformly distributed rectangular fins. The total charging–discharging time saved was about 4.7%, 11% and 14.2% for the three structures compared with uniformly distributed rectangular fins. The addition of nanoparticles could further reduce the melting time and solidification time. The applications of dendritic fins in LHTES units are summarized in Table 3.

Table 3. Applications of dendritic fins in LHTES units.

References	Year	Pipe Types	Exp/Num	Melting/Solidification	PCM	Findings Description
Sciacovelli et al. [78]	2015	Single-tube	N	S	Paraffin wax	Both single and double two-level dendritic fins could promote the solidification of PCM, and the double bifurcation two-level dendritic fins improved the discharging efficiency about 24%.
Zhao et al. [79]	2020	Single-tube	N	M	RT 82	The rectangular fins with unequal length showed the best performance compared with rectangular fins with unequal interval and two-level dendritic fins on the melting process in horizontal heat storage unit.
Safari et al. [80,81]	2021	Single-tube	E/N	M	Paraffin wax	The addition of two-level dendritic fins and pipe eccentricity could increase the melting rate, and the performance of dendritic fins was better than that of rectangular fins.
Wu et al. [7]	2020	Single-tube	N	M/S	Lauric acid	Dendritic fins obviously reduced the solidification time compared with rectangular fins, but had little effect on the melting time.
Zheng et al. [77]	2020	Single-tube	N	S	Water	More uniform solidification front and faster solidification speed were achieved using dendritic fins instead of rectangular fins. The four-level dendritic fins reduced the solidification time by 53%.
Yu et al. [82]	2020	Single-tube	N	M	Lauric acid	The melting time reduced about 26.7% compared to dendritic fins with rectangular fins at the same volume.
Huang and Liu [83]	2021	Single-tube	N	M/S	Lauric acid	Dendritic fins reduced melting/solidification time about 34.5%/49.2%, and improved the time average heat storage/release power about 49.4%/96.4%.
Vogel and Johnson [84]	2019	Single-tube	N	M	$NaNO_3$	Increasing fin branch was beneficial to the development of natural convection.
Asgari et al. [85]	2021	Single-tube	N	S	Water	Thin and long dendritic fins could improve the heat transfer.
Hosseinzadeh et al. [86]	2019	Single-tube	E/N	S	Water	Increasing the fin branch angle accelerated the solidification process.
Liu et al. [87]	2020	Single-tube	N	M	Lauric acid	Non-uniform dendritic fins increased the melting rate due to the enhancement of heat conduction and natural convection. Best performance appeared at fill angle of 300° and central-angle gradient of 8°.
Peng et al. [88]	2022	Single-tube	N	M	N-octadecane	The existence of dendritic fins significantly accelerated the melting process, and the increase in melting rate increased with the increase in branch angle.
Huang et al. [89]	2022	Single-tube	E/N	M/S	Lauric acid	The non-uniform arrangement of gradient tree-like fins improved the heat transfer performance during melting process, but was not conducive to the solidification process dominated by heat conduction.
Huang et al. [90]	2021	Single-tube	E	M/S	Lauric acid	The inclination of heat storage devices had more apparent effect on the melting process than the solidification process, and excessive inclination angle played a negative effect. The device with dendritic fins was slightly affected by the inclination angle.
Huang et al. [91]	2021	Single-tube	N	M	RT 82	The proposed graded fin on the basis of the dendritic fin decreased the melting time compared with the ordinary structure through improving the heat conduction effect in the later melting stage.
Huang et al. [92]	2022	Multi- tube	N	M/S	Lauric acid	Dendritic fins effectively improved heat transfer and temperature uniformity. The melting time of a vertical device was 46.3% shorter than that of a horizontal device.
Song et al. [93]	2022	Multi- tube	N	M	Lauric acid, RT58, and $NaNO_3$	The melting time reduced about 80.2% and 34.4% using dendritic fins instead of finless structure and rectangular fins, respectively.
Alizadeh et al. [94]	2020	Triplex tube	N	S	Water	The solidification time could be reduced by decreasing the trunk length of the fin or increasing the branch length and angle.
Hajizadeh et al. [95]	2020	Triplex tube	N	S	Paraffin RT35	Two proposed configurations reduced solidification time about 64.5% and 70.06%, respectively.

Table 3. *Cont.*

References	Year	Pipe Types	Exp/Num	Melting/Solidification	PCM	Findings Description
Li et al. [96]	2020	Triplex tube	N	S	N-octadecane	The melting time reduced by using fins on inner and outer walls of middle layer simultaneously. Longer fins were more helpful to the heat transfer enhancement.
Zhang et al. [97]	2020	Triplex tube	N	M/S	Lauric acid	The melting and solidification time reduced about 4.4% and 66.2% when using dendritic fins.
Hosseinzadeh et al. [98]	2021	Triplex tube	N	S	Water	The solidification time reduced about 51.4% using dendritic fins instead of rectangular fins, and further reduction to 78% was achieved through the combination of dendritic fins and nanoparticles.

2.7. Other Fins

In addition to the fin structures summarized above, there are also some other less-studied or innovative fins, such as V-shaped fin, triangular fin, etc. V-shaped fin is similar to the rectangular fin, and it could be considered as a combination of two rectangular fins with a certain angle. Lohrasbi et al. [102] numerical investigated the solidification process of LHTES system with V-shaped fins shown in Figure 11. There was an optimal fin direction leading to the fast solidification rate. Increasing both the thickness and length of the fin could improve the heat transfer performance during the solidification process, and the fin length showed more significant influence. They optimized the V-shaped fin based on the optimization objective of minimizing the discharging time and maximizing the heat storage capacity [103]. The discharging time was accelerated 5.749 times when using the optimized V-shaped fins instead of finless structure. Sheikholeslami et al. [104] found that the solidification rate of PCM increased with the increase in fin angle and was inversely proportional to the fin length for a V-shaped fin structure through numerical investigation. Mahdi et al. [105] optimized the V-shaped fin structure in a triplex tube LHTES unit through response surface method. They found that the optimized fin structure was better than nanoparticles on improving the heat storage rate. Alizadeh et al. [106] adopted a V-shaped fin and nanoparticles to enhance the heat transfer of solidification process of PCM in a triplex tube LHTES unit. The results showed that structures with large fin length or moderate fin angle could accelerate the solidification process, whereas the fin thickness showed slight effect. In addition, the V-shaped fin structure was more effective to improve the solidification rate compared with nanoparticles.

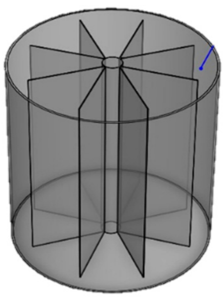
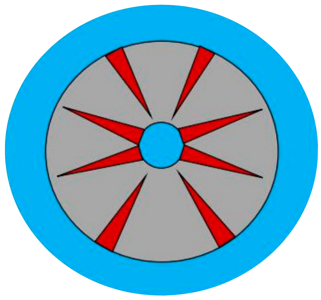
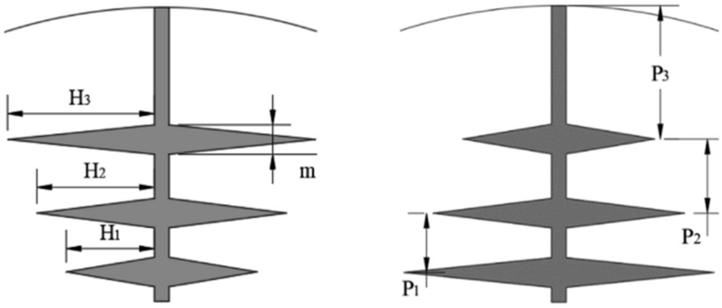


Figure 11. V-shaped fin [102]. (Permission to reproduce from Ref. [102]).

Abdulateef et al. [107–109] experimentally and numerically investigated the performance of triplex tube LHTES units with triangular fins similar to Figure 12a. Six kinds of fin structure were proposed: internal triangular/rectangular fins, external triangular/rectangular fins, and internal–external triangular/rectangular fins. The maximum reduction of about 15% in melting time and 18% in solidification time appeared when using the internal–external triangular fin structure. Yao and Huang [110] studied the effect of different longitudinal triangular fin structures in triplex tube heat storage system, as shown in Figure 12b. The structure on the left side of Figure 12b played better performance compared with rectangular, which reduced the solidification time about 30.98%. The solidification time decreased, apparently with the increase in fin length. Qaiser et al. [111] compared the performances of different tube shapes on the LHTES unit. The triangular shape with the vertex pointing downward showed the best performance compared with hexagonal, pentagonal, and square shapes, which improved the melting rate of PCM about 27.2% compared with base circular shape.



(**a**)



(**b**)

Figure 12. Different triangular fins. (**a**) Internal–external triangular fins [107]; (**b**) Longitudinal triangular fins [110]. (Permission to reproduce from Refs. [107,110]).

Aly et al. [112] numerically studied the influence of longitudinal corrugated fins (Figure 13a) on the solidification process of PCM in the heat storage device. The solidification time was reduced about 30–35% through increasing the number of corrugations or fin length. However, the effectiveness of corrugated fins was lower than that of rectangular fins. Wu et al. [113] numerically studied the influence of spiderweb-like fins (Figure 13b) on the solidification process of PCM in the LHTES device. The results showed that the spiderweb-like fin could eliminate the heat transfer hysteresis zone. The complete solidification time was reduced about 47.9% when a spiderweb-like fin with 8 bifurcations was used. Ma et al. [114] numerically studied the influence of circular superimposed longitudinal fins (Figure 13c) on the heat release process of the LHTES device. It is found that the circular superposed fin with decreasing diameter was the best structure, which could reduce the solidification time about 38.72% compared with the rectangular fin. Al-Mudhafar et al. [115] analyzed the influences of finless structure, rectangular fins, T-shaped fins and double T-shaped fins (Figure 13d) on the melting process of PCM in the LHTES unit. It was found that T-shaped fins reduced the melting time of PCM by 33% compared with rectangular fins, due to the increase in heat penetration depth and heat transfer surface area. Pahamli et al. [116] proposed a blossom-shaped fin structure (Figure 13e). Increasing the fin number improved the melting rate and exergy efficiency. The melting time reduced about 2% and the exergy efficiency decreased by 8% when the fins are sparse in the upper part and compact in the lower part. The decrease in fin length was helpful to improve the exergy efficiency and prolong the melting time. Mao et al. [117] proposed a new fan-shaped fin structure to enhance the energy utilization rate. Three fan shaped fin structures were evolved from the basic structure. The numerical results showed that the complete melting time of PCM in Fan-A tube, which was similar to the structure shown in Figure 13e, was reduced about 5.3%, 14.6% and 11.6% compared with basic structure, Fan-B and Fan-C.

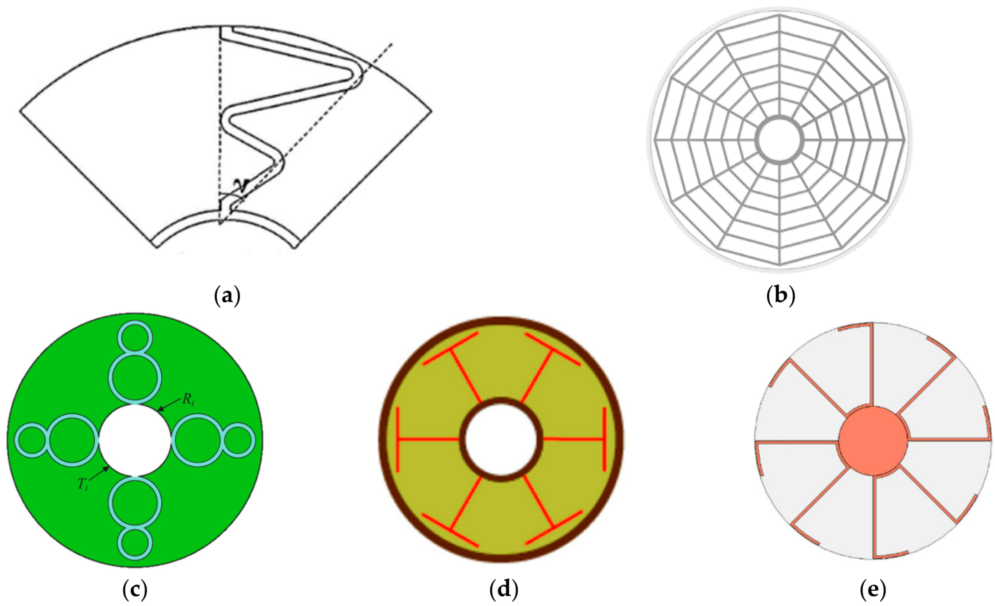


Figure 13. Different innovative fins. (a) Longitudinal corrugated fin [112]; (b) Spiderweb-like fin [113]; (c) Circular superimposed longitudinal fin [114]; (d) T-shaped fin [115]; (e) Blossom-shaped fin [116]. (Permission to reproduce from Refs. [112–116]).

3. Comparison between Different Fin Structures

With the increase in fin types, how to choose the fin structure for the LHTES device has become a problem. Longitudinal rectangular fins are often used to compare with new types of fins. Some researchers have also analyzed the similarities and differences between other types of fins.

Agyenim et al. [118] compared the effects of finless structures, annular fins and rectangular fins. The heat storage time was the shortest and the supercooling degree of PCM was small during the heat release process when using a rectangular fin structure in the experiment. The results also proved that it was reasonable to ignore the axial heat conduction in the current commonly used numerical models. Hassan et al. [119] found that the rectangular fins and annular fins reduced about 55% and 70% of the melting time, respectively, compared with finless structures. Tiari and Hockins [120] compared the performances of 10 and 20 annular fins with those of 4 and 8 rectangular fins at the same volume. The 8 rectangular fins showed the best performance, which reduced the heat storage and release time by 86.6% and 80.1%, respectively.

Zhang et al. [121] compared rectangular fins, annular fins and spiral fins. Double helical fins with vertical orientation and quadruple helical fins with horizontal orientation (Figure 14) reduced the melting time by 31.0% and 10.0%, respectively, compared with rectangular fins. Mostafavi et al. [122] investigated annular fins and Cartesian fins. The results showed that there was an optimal size for Cartesian, which significantly affected the heat transfer performance. For annular fins, even thin fins could enhance the heat transfer. Dekhil et al. [123] found that the heat transfer enhancement of rectangular fins was better than that of annular fins, considering the influence of water density variation on flow and heat transfer characteristics during phase change. Jannesari and Abdollahi [124] compared the effects of staggered ring fins (Figure 15) and annular fins on heat storage devices using water as PCM. The staggered ring fins have better heat transfer performance than annular fins, which improved 15% icing speed compared with finless structures. Khan and Khan [125] compared the effects of rectangular fins, annular fins and wire-wound fins (Figure 16) on heat transfer enhancement. The three kinds of fin structures reduced the melting time by 84.3%, 87.3% and 90.9%, respectively, compared with the finless structure. In addition, annular fins weaken natural convection more obviously than rectangular and wire-wound fins.

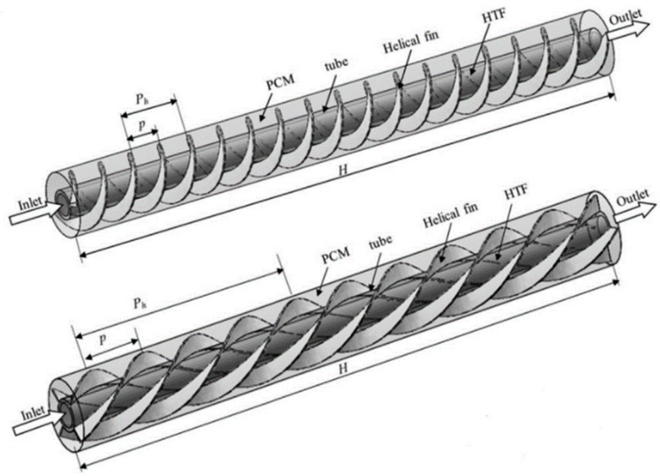


Figure 14. Double helical fins and quadruple helical fins [121]. (Permission to reproduce from Ref. [121]).

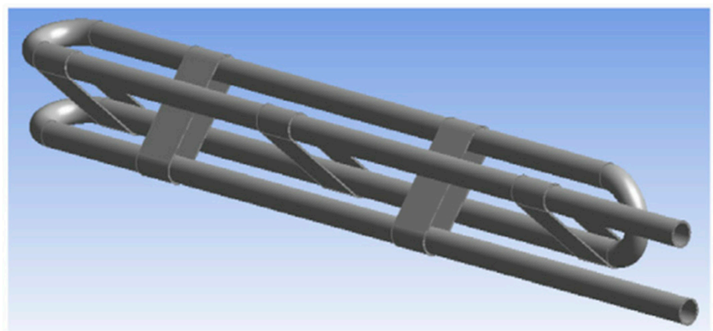


Figure 15. Staggered ring fins [124]. (Permission to reproduce from Ref. [124]).

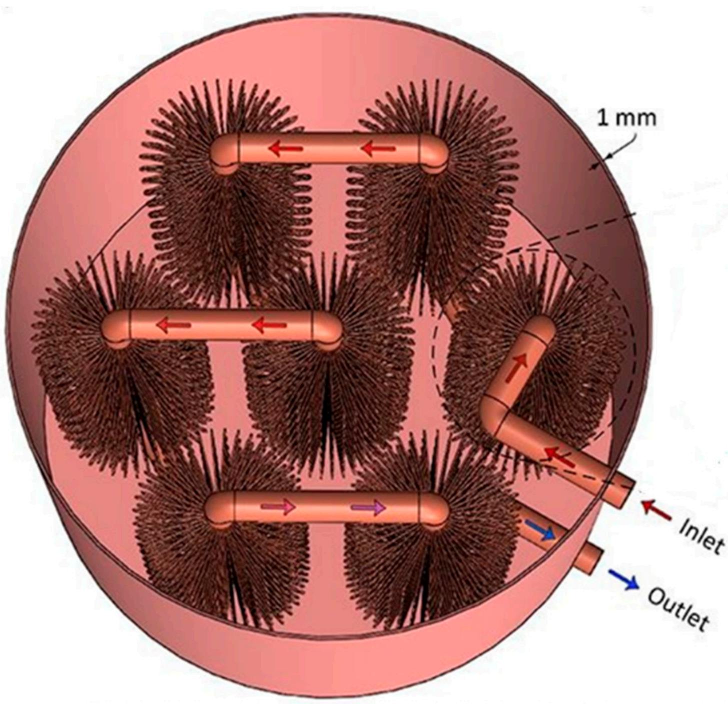


Figure 16. Wire-wound fins [125]. (Permission to reproduce from Ref. [125]).

4. Conclusions and Perspective

LHTES is one of the most attractive heat storage technologies. However, the low thermal conductivity of PCM limits its heat storage and release performance. Using fin tube is an effective method to enhance the heat transfer of LHTES systems. There have been numerous investigations reported about the effect of different fin structures. In this paper, the research of fin structure on the heat transfer enhancement of LHTES system is summarized according to the types of fins, such as rectangular fin, annular fin, spiral fin, plate fin, topology optimized fin, dendritic fin and other fins.

For most types of fin, the parameters affecting the heat transfer performance include fin number, length (diameter), thickness, angle, position and arrangement. In general, increasing the fin number and length (diameter) could apparently reduce the phase change time, whereas the heat storage capacity also decreases. There is no or negative effect on heat transfer performance when increasing the fin thickness. The effect of fin angle depends on the fin type and the arrangement. Rectangular fins usually show better performance than annular fins. The heat transfer performance of complex or innovative fins is generally better than that of rectangular fins at the same volume. However, rectangular fins are the most widely used fin type due to their simple structure, ease of manufacture and low cost.

The optimization of fin structure includes parameter optimization and shape optimization. The former focuses on optimizing the fin parameter such as length, number, thickness, etc. The latter is usually realized through perforating or slitting fins. The parameter and shape of fins in a LHTES system should be optimized as a whole, which considers the enhancing effect of fins on the heat conduction of PCM and its suppressing effect on the natural convection of liquid PCM. In addition, the topology optimization, which has less constraint, is a promising method to obtain the best fin structure, although the topology-optimized fin structure is not suitable for mass production.

Some other technologies, such as adding nanoparticles, attaching metal foam, adopting heat pipe, etc., are proposed to combine with fin structure. The cascaded heat storage is also one of the heat transfer enhancement methods, which could be combined with fin structure in the future. Better heat transfer performance can usually be achieved through the combination of different means. However, there are less investigations about the new combination enhancement means except adding nanoparticles, and it is a potential field for future research.

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