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Article

Rotation-based heat transfer enhancement for shell-and-tube latent thermal energy storage systems: From mechanisms to applications

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Abstract: Latent thermal energy storage (LTES) is an important energy storage technology to mitigate the discrepancy between energy source and energy supply, and it has great application prospects in many areas, such as solar energy utilization, geothermal energy utilization and electricity storage. However, LTES systems suffer from the low thermal conductivity of most phase-change materials (PCMs), threatening their large-scale commercial applications. To tackle this challenge, heat transfer enhancement for LTES systems is critically important and has been widely investigated worldwide. Convectional heat transfer enhancement techniques, including fins, nanoparticles and multiple PCMs, can significantly improve the charging and discharging rates of an LTES system. Recently, rotation-based methods have emerged to provide new routes for the heat transfer enhancement of LTES systems, and many achievements have been obtained by researchers around the world. This study conducted a short review of the mechanisms and applications of three rotation-based heat transfer enhancement methods, aiming to provide deep insights into these novel heat transfer enhancement methods and propel their future development and applications.

Keywords: latent thermal energy storage; phase-change materials; heat transfer enhancement; rotation

1. Introduction

Carbon neutrality has been a worldwide pursuit due to the increasingly urgent energy crisis and environmental pollution caused by the excessive use of fossil fuels [1,2]. Efforts to relieve greenhouse effects and control the temperature rise within 1.5 K in 2050 have propelled the large-scale utilization of renewable energies, such as solar energy, wind energy and geothermal energy [3,4]. However, renewable energies generally possess fluctuating and intermittent characteristics, leading to the unsteady operation of energy systems and the discrepancy between the energy source and energy demand in aspects of time and space [5]. Therefore, incorporating energy storage within existing energy systems is a promising solution to tackle this challenge [6].

Latent thermal energy storage (LTES) is one of the most important energy storage technologies to balance the mismatch between the energy supply and end-user energy demand, owing to its relatively high energy storage density, technical maturity and low cost [7], and it has been widely used in solar energy utilization [8,9], fluctuating waste heat recovery [10,11], Carnot batteries [12,13], etc. Nevertheless, LTES systems still suffer from the low thermal conductivity of most phase-change materials (PCMs) at the present stage [14,15]. The thermal conductivity of PCMs determines the heat transfer rate during charging and discharging processes, further affecting the energy storage efficiency of LTES systems in real applications. Researchers have conducted a great many studies concerning the heat transfer enhancement of LTES systems, and the representative convectional and emerging heat transfer enhancement methods are collected in **Figure 1**. Convectional heat transfer enhancement methods include the use of various types of fins [16,17], highly conductive additives (such as nanoparticles and metal foam) [18,19], heat pipes [20,21] and a cascaded layout of the PCM [22,23]. Although these methods present good heat transfer enhancement effects, they still suffer certain problems, such as the dispersibility and deposition of nanoparticles [24–26]. Recently, heat transfer enhancement methods that are dependent on external fields, such as magnetic field [27,28] and electric field [29,30], have emerged and have been investigated in LTES systems, especially rotation-based methods [31]. For convectional heat transfer enhancement methods, the number of fins, the concentration of nanoparticles or the segments of multiple PCMs cannot be adjusted to adapt to the charging and discharging processes once designed [32,33]. On the contrary, rotation-based methods are more flexible and active, which can regulate the charging and discharging processes by adjusting rotation conditions, such as rotation speed and direction, at any stage [34]. The particular advantages of rotation-based methods enable LTES systems to adapt to various heat source conditions and achieve higher overall charging and discharging rates, especially with fluctuating heat sources, since the charging process of LTES systems is more nonuniform during the discharging process [35–37]. Therefore, rotation-based methods exhibit great prospects in the adjustable heat transfer enhancement of small-scale LTES systems used in domestic and commercial applications.

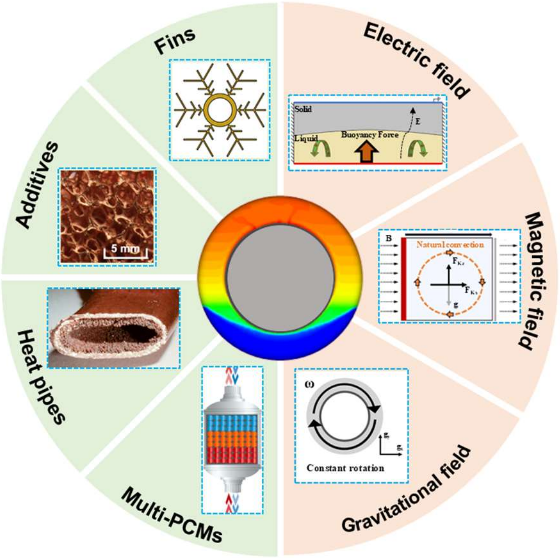

Figure 1. Active and passive heat transfer enhancement methods in LTES system.

For rotation-based heat transfer enhancement methods, there are various implementation modes, such as the continuous rotation of an entire LTES system, the continuous rotation of a heat transfer fluid (HTF) tube and the flipping of an entire LTES system, and each of them achieves the effects of heat transfer enhancement by triggering or enhancing the natural convection of the liquid PCM inside the LTES system. For the continuous rotation mode of the entire LTES system, the effects of heat transfer enhancement are affected by various parameters, including rotation speed, rotation direction, duration of rotation, timing of rotation, etc. Similar issues also exist in other rotation modes. Focusing on the mechanisms, effects, applications and limitations of rotation-based heat transfer enhancement methods under various operating parameters in LTES systems, a great deal of numerical and experimental studies has been conducted and great achievements have been obtained in recent years. In view of these advances, it is important to analyze and conclude the underlying mechanisms of rotation-based heat transfer enhancement methods associated with various rotation modes and operating parameters in order to provide guidelines for future designs and applications of rotation-based methods in LTES systems. By conducting the above-mentioned analysis, this review aimed to answer the following questions related to rotation-based heat transfer enhancement methods for shell-and-tube LTES systems: (1) why rotation-based methods are important to the heat transfer enhancement of LTES systems, (2) how rotation-based heat transfer enhancement methods efficiently work and (3) what routings can be utilized to optimize the operating parameters for achieving cost-effective and convenient rotation-based heat transfer enhancement methods.

2. Principles of rotation-based heat transfer enhancement

2.1. Challenges of heat transfer enhancement in LTES systems

During the charging process of a shell-and-tube LTES system, the PCM in the shell side undergoes an inconsistent melting process at different regions, especially at the bottom and top regions. As shown in **Figure 2a**, the solid PCM at the top region melts much faster than that at the bottom region due to the natural convection of the liquid PCM that melted before, and the low thermal conductivity of most PCMs further enlarges the difference of the melting process. Therefore, the distributions of temperature and velocity are not uniform across the whole shell side. During the whole charging process, the charging rate and liquid volume fraction are also not linear, as shown in **Figure 2b**, owing to the variation of the dominant heat transfer mechanisms inside the PCM. In detail, in the early stage, the melting process is dominated by natural convection with a larger heat transfer rate, and the liquid volume fraction presents a remarkable increasing trend. In the later stage, the melting process is dominated by conduction with a small heat transfer rate, which is restricted by the low thermal conductivity of most PCMs, and the liquid volume fraction shows a moderate increase. Overall, the natural convection of liquid PCMs leads to the nonuniform charging process of an LTES system, and the low thermal conductivity of most PCMs further deteriorates the nonuniform temperature distribution, resulting in a low charging rate, low energy storage efficiency and long melting time for LTES systems during the charging process. As for the discharging process, the natural convection in liquid PCMs is weak and the discharging rate is less influenced by natural convection. However, the discharging rate can be enhanced if natural convection in the liquid volume fraction intensifies during the discharging process. Hence, regulating the natural convection of a liquid PCM during the charging and discharging processes determines the charging and discharging performances of an LTES system, and this is the advantage of rotation-based heat transfer enhancement methods.

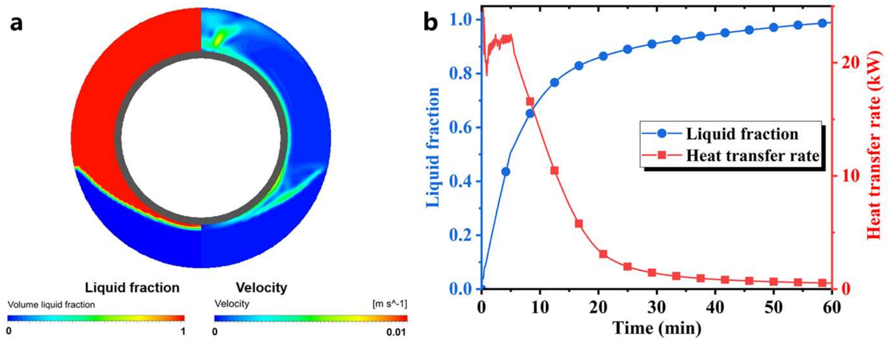

Figure 2. Nonuniform melting process of shell-and-tube LTES system during charging: **(a)** distribution of temperature and velocity and **(b)** heat flux and liquid volume fraction.

2.2. Classifications and working principles of rotation-based methods

To eliminate the nonuniform charging process of LTES systems and sufficiently utilize natural convection, the use of rotation-based methods is important to enhance the heat transfer rate. The rotation could stimulate the convection inside the liquid PCM, and the heat transfer process of the PCM originally located in the lower part of the LTES can be improved by rotating to the upper part. According to recent studies, rotation-based methods are generally classified into three modes: (1) the continuous rotation of an entire LTES system (2) the continuous rotation of an HTF tube and (3) the flipping of an entire LTES system. For the first mode, the entire LTES system is continuously rotated around the horizontal or vertical axis. The continuous rotation can rotate hard-to-melt areas originally at the lower part of the LTES system to the upper part to enhance the natural convection in the liquid PCM. For the second mode, the continuous rotation of a heat transfer tube starts to work when enough of the liquid PCM forms during the charging process and induces the occurrence and intensity of natural convection. During the discharging process, the continuous rotation of the heat transfer tube with scrapers can scrape the solidified PCM on the surface of the heat transfer tube, thus enhancing the heat transfer rate. For the third mode, the entire LTES can be rotated step by step at a certain angle to change the relative locations of fast-melting areas and hard-to-melt areas inside the LTES system, thus utilizing natural convection in hard-to-melt areas. When the step-rotation angle is 180°, the step rotation is called flipping. Flipping has the potential to achieve comparative or even better heat transfer enhancement effects with lower parasitic power compared with those of the continuous rotation mode.

3. Advances in rotation-based methods in LTES systems

As specified in the previous section, there are different rotation modes, which are the continuous rotation of an entire LTES system, the continuous rotation of a heat transfer fluid tube and the flipping of an entire LTES system. Each of them possesses individual advantages, which will be separately discussed in this section.

3.1. Continuous rotation of entire LTES system

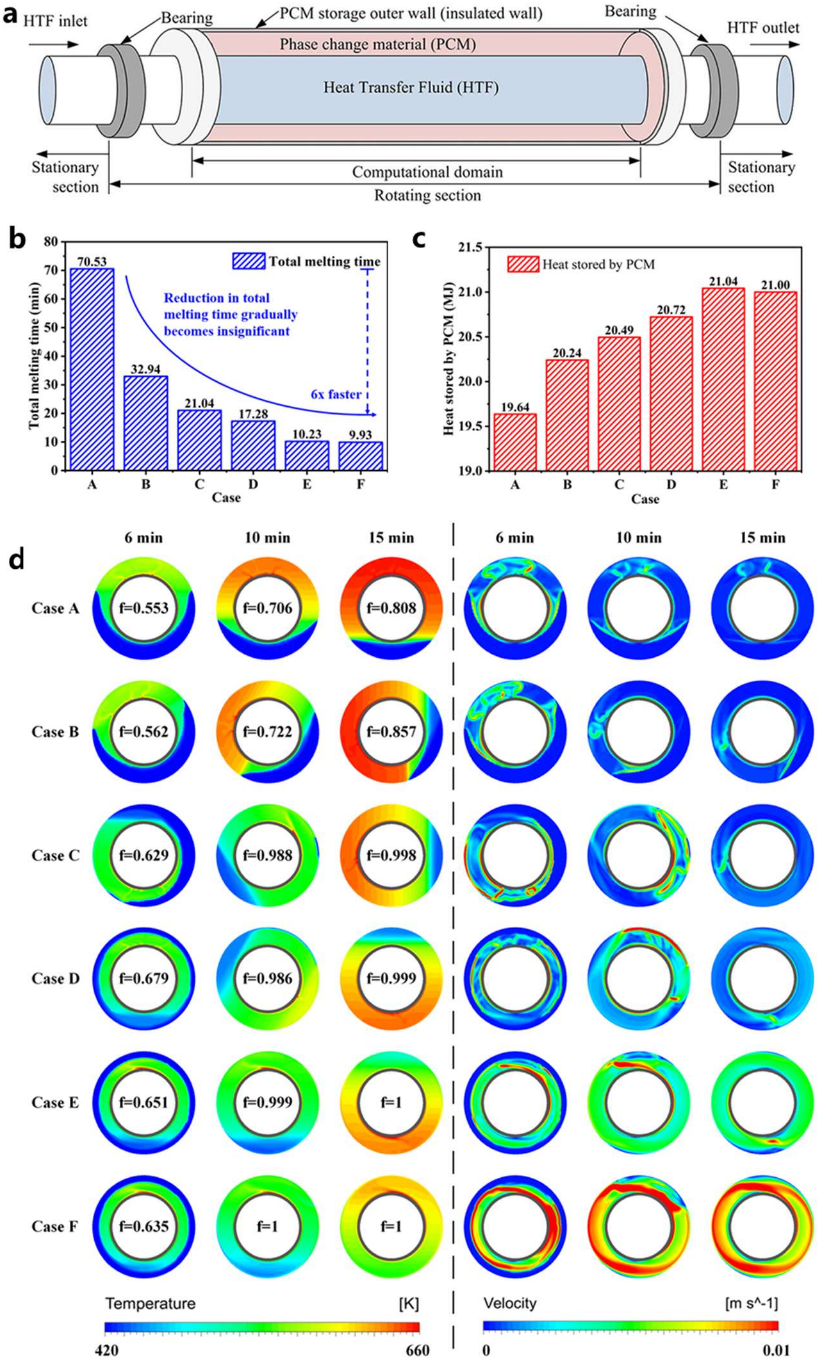

Figure 3. Continuous rotation of entire LTES system: **(a)** schematic diagram of rotating shell-and-tube LTES system [39]; **(b)** total melting time at various rotation speeds [40]; **(c)** heat stored by PCM at various rotation speeds [40]; **(d)** temperature and velocity of shell-and-tube LTES system under various rotation speeds [40].

Rotation was first used in the heat transfer enhancement of shell-and-tube LTES systems [38]. The effects of heat transfer enhancement attributed to continuous rotation are affected by some key parameters, including the rotation speed and rotation direction. Kurnia and Sasmito [39] designed a shell-and-tube LTES system with a rotating function, as shown in **Figure 3a**, and the charging and discharging performances under different rotation speeds were numerically investigated. The results demonstrated that rotation enhanced the heat transfer rate of the LTES system during the charging and discharging processes, and the enhancement ratio increased at higher rotation speeds due to the stronger natural convection in the liquid PCM. Quantitatively, the LTES system under rotation achieved up to 25.2% and 41% higher heat transfer rates during the charging and discharging processes, respectively, compared with those of the LTES system under a static condition. In addition, the results indicated that the heat transfer enhancement effects were more significant when sufficient PCM melted for stronger natural convection. Yu et al. [40] demonstrated the positive effects of continuous rotation on enhancing the heat transfer rate and heat storage capacity of a shell-and-tube LTES system. The results indicated that the rotating LTES system achieved 6 times faster heat transfer rate and a larger heat storage capacity, as shown in **Figure 3b** and **Figure 3c**, and the reason was the stronger natural convection and the more uniform temperature field, as shown in **Figure 3d**. Based on the above-mentioned results, although rotation speed has significant effects on the heat transfer enhancement of LTES systems, the heat transfer enhancement effects increase slightly after the rotation speed reaches a critical value. In addition, a higher rotation speed means a higher parasitic power consumption of the whole rotation system.

As an active heat transfer enhancement method, rotation has also been combined with other passive heat transfer enhancement methods in shell-and-tube LTES systems, especially via various kinds of fins. Soltani et al. [41] investigated the heat transfer enhancement effects of a finned-tube LTES system at various rotation conditions. It was found that the addition of fins reduced natural convection, and the employment of rotation eliminated the sedimentation phenomenon of the PCM and enhanced natural convection. The results also demonstrated that increasing the number of fins attenuated the heat transfer enhancement effects of rotation. Therefore, the combined application of fins and rotation should consider the design and optimization of parameters, such as fin number and rotation speed. Some authors systematically analyzed the roles of rotation in enhancing the charging and discharging performances of a triple-tube LTES system with fins [42–46]. **Figure 4** presents the schematic diagram of a rotating triple-tube LTES system with fins. For the discharging process of the triple-tube LTES system under rotation, the results indicated that rotation changed the heat transfer mode from single heat conduction to combined heat conduction and natural convection [45,46], resulting in a faster solidification rate and more uniform temperature distribution, as shown in **Figure 5**. The solidification rate increased with the rise in rotation speed. Quantitatively, compared with those of a static LTES system, the solidification time of the rotating LTES system was reduced by 46% and 83.9% and the discharging rates increased 3.3 times and 5 times at rotation speeds of 0.05 rpm and 1 rpm, respectively. For the charging process of the triple-tube LTES system under rotation, the rotation eliminated the thermal deposition at the upper part of the LTES system caused by natural convection and enhanced the intensity of natural convection and the charging rate [42]. The results showed that the melting times of the LTES system at 0.1 rpm and 1 rpm were 46.98% and 69.35% lower than those of a static LTES system [43]. The above-mentioned studies demonstrated that rotating the whole LTES system is an efficient method to significantly enhance the charging and discharging rates of shell-and-tube LTES systems with or without fins due to the effects on the natural convection of the liquid PCM. For LTES systems with fins, natural convection is generally reduced by the fins, but the mechanisms of heat transfer enhancement by rotation improve natural convection. Studies have optimized the fin parameters and the rotation speed from the macroscopical perspective [44,47,48], and the coupling effects between the fins and rotation on the charging and discharging mechanisms, especially their effects on the occurrence and elimination of natural convection, have not been clearly revealed, and this deserves more efforts in the future.

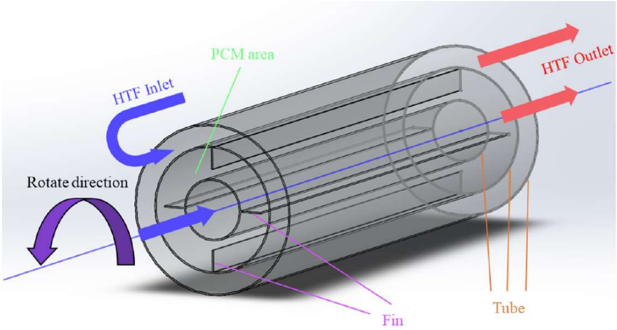

Figure 4. Schematic diagram of rotating triple-tube LTES system with fins [46].

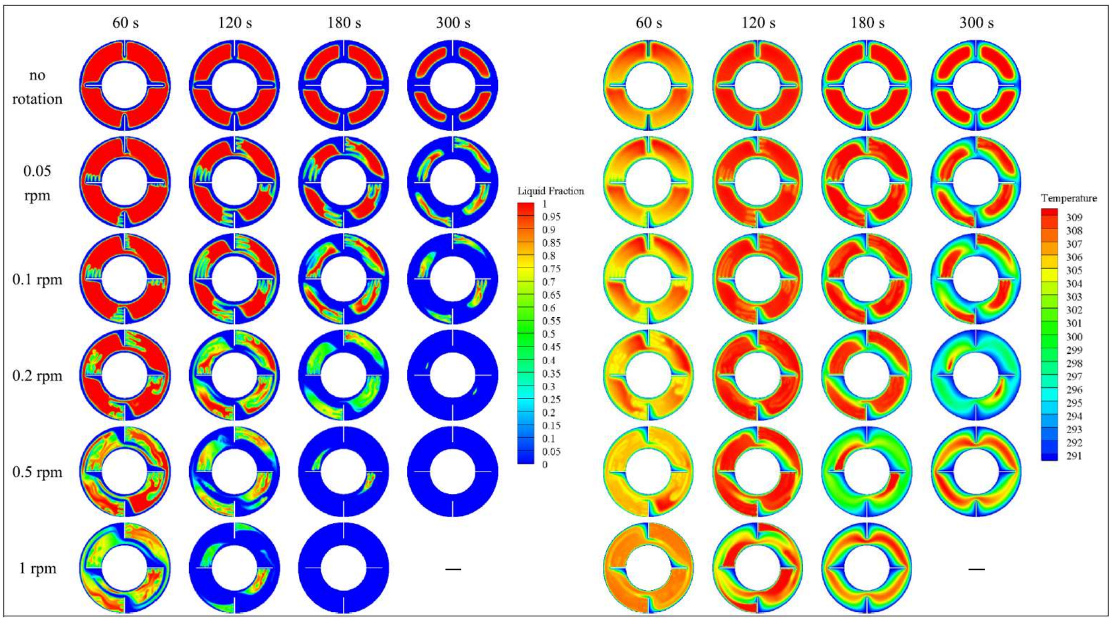

Figure 5. Evolution of liquid fraction and temperature under different rotation speeds [46].

Rotation has also been combined with other passive heat transfer enhancement methods, such as using nanoparticles [49], metal foam [50–53] and an eccentric heat transfer fluid tube [54,55], in shell-and-tube LTES systems. Huang et al. [49] investigated the effects of nanoparticle mass ratio and rotation speed on the charging process of a triple-tube LTES system with longitude fins. It was proved that the LTES system incorporated with 2.5% and 5% Al_2O_3 nanoparticles at the rotation speed of 0.1 rpm achieved 58.5% and 57.6% shorter melting times and 126.5% and 123.4%

higher charging rates, respectively, than those of the basic case without nanoparticles and rotation, which implied that the larger concentration of nanoparticles led to an inferior discharging performance. More importantly, from Taguchi analysis, this study also claimed that rotation speed had a larger influence than nanoparticle concentration. For the application of metal foam, Huang et al. [50] focused on the effects of pore density and porosity of metal foam on the charging process of a triple-tube LTES system under constant rotation, and it was found that the LTES system with metal foam showed a larger charging rate and more uniform temperature distribution, as shown in **Figure 6**. Some studies [51–53] highlighted the importance of metal foam's porosity range, metal foam's grade layer and rotation speed to the charging and discharging performances of an LTES system, and it was demonstrated that there were optimal values for these critical parameters to achieve the best charging and discharging performances. While the above-mentioned studies also paid attention to the effects of various parameters, such as metal foam's porosity and rotation speed, on the charging and discharging performances of an LTES system, the coupling mechanisms between metal foam and rotation to enhance the heat transfer process have not been thoroughly investigated. Hence, such research is important to provide guidelines for the design of rotation conditions, including rotation speed and rotation direction.

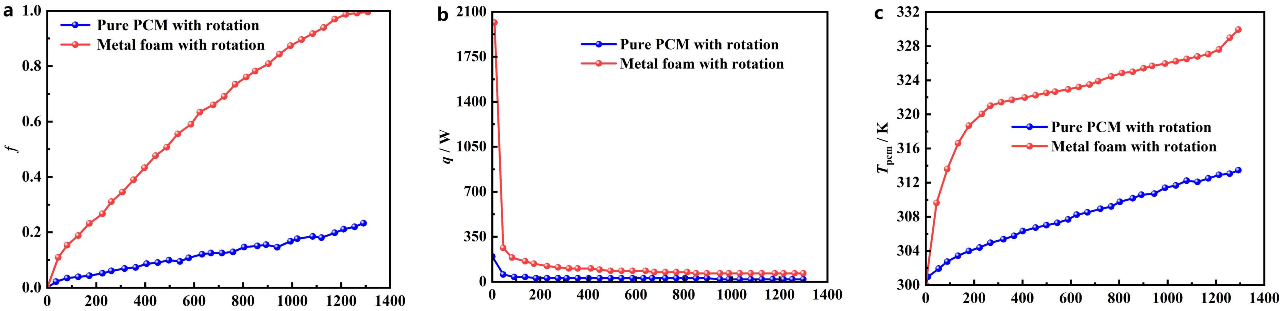

Figure 6. Comparison of melting properties from rotating LTES systems with pure PCM and with metal foam: **(a)** liquid phase rate change; **(b)** instantaneous heat storage rate and **(c)** average temperature of PCM [50].

The studies on the continuous rotation of the entire LTES system for heat transfer enhancement are presented in **Table 1**, and the evaluated parameters, charging/discharging process, research methods and heat transfer types are summarized. It can be found that most of the studies conducted numerical simulations, and very few studies experimentally demonstrated the effects of continuous rotation. One of the most important technical challenges is the realization of the rotation of an entire LTES system when employing rotation for heat transfer enhancement. Therefore, the design of a proper rotation prototype is meaningful and critical. Yang et al. [56] designed a test rig with a rotation function for a shell-and-tube LTES system, as shown in **Figure 7a**. A rotary joint, driven by a motor, was used to connect the static and rotating parts. A slip ring was adopted to prevent sensor wires from winding other experimental devices. Rotation speed was adjusted by regulating the voltage and current of the motor. A similar test rig was designed by Fathi and Mussa [57], as shown in **Figure 7b**. Both rigs achieved the function of rotation and demonstrated the significant effects of heat transfer enhancement attributed to rotation, as compared with those of a static LTES system.

Table 1. Heat transfer enhancement by continuous rotation of entire LTES system.

Parameter	Process	Method	Heat transfer enhancement method	Ref.
LTES orientation, rotation speed	Charging, discharging	Simulation	Tube, rotation	[39]
Rotation speed, rotation modes	Charging	Experiment	Tube, rotation	[40]
Rotation speed, fin number,	Charging, discharging	Simulation	Finned tube, rotation	[41]
Rotation speed, rotation modes	Charging	Simulation	Finned tube, rotation	[47]
Rotation speed, rotation modes	Charging	Simulation	Finned tube, rotation	[58]
Rotation speed, fin number, fin angle	Charging	Simulation	Triple tubes, fins, rotation	[42]
Rotation speed, fin size, fin angle	Charging	Simulation	Triple tubes, fins, rotation	[43]
Rotation speed	Charging	Simulation	Triple tubes, fins, rotation	[44]
Rotation speed, fin size, fin angle	Charging	Simulation	Triple tubes, fins, rotation	[48]
Rotation speed, fin number, fin angle	Discharging	Simulation	Triple tubes, fins, rotation	[45]
Rotation speed, fin size, fin angle	Discharging	Simulation	Triple tubes, fins, rotation	[46]
Rotation speed, nanoparticle ratio	Charging	Simulation	Triple tubes, fins, nanoparticles, rotation	[49]
Pore density, porosity	Charging	Simulation	Triple tubes, metal foam, rotation	[50]
Porosity range, grade layer, rotation speed	Charging	Simulation	Tube, metal foam, rotation	[52]
Porosity range, grade layer, rotation speed	Charging	Simulation	Finned tube, metal foam, rotation	[53]
Concentration porosity, concentration ratio, rotation speed	Charging, discharging	Simulation	Tube, metal foam, rotation	[51]
Eccentricity angle, rotation speed	Charging	Simulation	Eccentric triplex-tube, rotation	[55]
Eccentricity value, eccentricity angle, rotation speed	Charging	Simulation	Eccentric triplex-tube, rotation	[54]
Rotation speed	Charging	Experiment	Tube, rotation	[56]
Rotation speed	Charging	Experiment	Tube, rotation	[57]

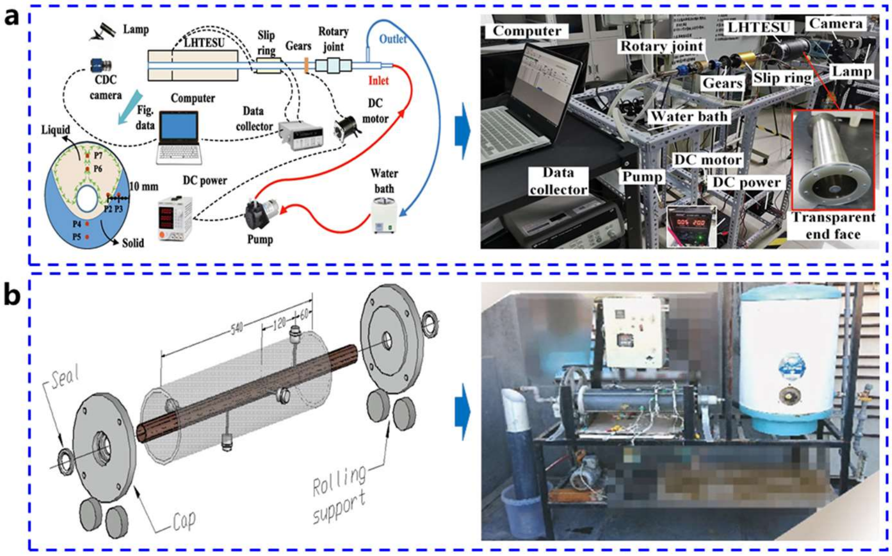

Figure 7. Schematic and physical diagrams of LTES test rigs with rotation function demonstrated by **(a)** Yang et al. [56] and **(b)** Fathi and Mussa [57].

It is proved by previous studies that continuous rotation can achieve higher charging and discharging rates and a more uniform temperature distribution in shell-and-tube LTES systems. Rotation can also be combined with other passive heat transfer enhancement methods, such as using fins, nanoparticles and metal foam. However, continuous rotation can also lead to higher parasitic power and more complex operating conditions, which require more complicated auxiliary devices. Therefore, it is important to further reveal the heat transfer enhancement mechanisms of rotation, especially the coupling mechanisms with other passive heat transfer enchantment methods, to provide guidelines for the simplification of rotation conditions, such as discontinuous rotation and variable rotation, in order to achieve the same and even better heat transfer enhancement effects.

3.2. Continuous rotation of heat transfer tube

Rotation-based methods have been considered to enhance the heat transfer process in conventional shell-and-tube LTES systems [59–61], and a typical schematic diagram is shown in **Figure 8a**. In this case, blades are fixed on a heat transfer tube and their function is to remove the boundary layer of heat transfer by scraping and to induce convection when the heat transfer tube rotates. In a shell-and-tube LTES system, the rotation of the heat transfer tube has also been employed to enhance the heat transfer process due to the low thermal conductivity of most PCMs [62,63]. However, the rotation of the heat transfer tube during the charging process of an LTES system was experimentally proved by Fathi and Mussa [62] to have marginal effects (up to 8%) on the charging rate when the rotation speed was lower than 9 rpm due to the minor effects of rotation on natural convection in the liquid PCM. Later, more studies focused on the effects of heat transfer tube rotation on the discharging process of LTES systems, since the solidified PCM on the outer surface of the heat transfer tube deteriorates the discharging rate of a LTES system due to the low thermal conductivity of most PCMs. Therefore, researchers explored the feasibility of the rotation of a heat transfer tube with a fixed scraper to scrape the solidified PCM on the outer surface of the heat transfer tube and thus enhance the discharging rate. Maruoka et al. [64] experimentally investigated the discharging performance of a shell-and-tube LTES system with a scraper fixed on a heat transfer tube. The results proved that the discharging rate of the LTES system under rotation was 100 times higher than that of a static LTES system, and the discharging rate increased with the rise in rotation speed. However, the high discharging rate only lasted until the liquid volume fraction reached 30%, since the low liquid volume fraction prohibited the working of the scraper fixed on the heat transfer tube.

Some authors conducted a series of studies to analyze the discharging performance of shell-and-tube LTES systems enhanced by the rotation of a heat transfer tube with a scraper [65–67]. A test rig was designed and the schematic diagram is shown in **Figure 8b**. The liquid PCM solidified on the outer surface of the heat transfer tube during the discharging process, and then it was removed by the fixed scraper when the heat transfer tube rotated. The experimental results [65] also highlighted the importance of rotation speed to the scraping of the solidified PCM, as shown in **Figure 8c**. Heat transfer enhancement effects are also affected by several temperature differences, which include the temperature differences between the heat transfer fluid and the liquid PCM, between the heat transfer fluid and the melting point, and between the liquid PCM and the melting point. These temperature differences have an influence on the thickness of the solidified PCM and thus affect the rotation of the heat transfer tube. Due to the inconvenience of investigating the effects of these parameters via experiments, Tombrink and Bauer [66] developed a numerical model to design the operating parameters, and the model was validated by experimental data, as shown in **Figure 8**. Based on the numerical model and an experimental test rig, Tombrink and Bauer [67] designed a rotating shell-and-tube LTES system with a rotating heat transfer tube fixed with a scraper for a pure steam generation system and a steam-and-electricity cogeneration system driven by renewable energies, which showed a high volumetric energy storage density and surface heat transfer coefficient, indicating the great potential of rotating shell-and-tube LTES systems in utilizing fluctuating renewable energies. Based on the above-mentioned rotating shell-and-tube LTES systems, some modifications have been made for other applications. Egea et al. [68] designed a rotating shell-and-tube LTES system for a domestic hot water supply. Low-temperature water flowed through the outer heat transfer tube, while the PCM was packed in the inner tube. Scrapers were fixed on the inner tube to scrape the solidified PCM when preparing the hot water. The experimental result indicated that the rotating LTES system with scrapers increased the energy extraction rate to 95% from 62% without scrapers.

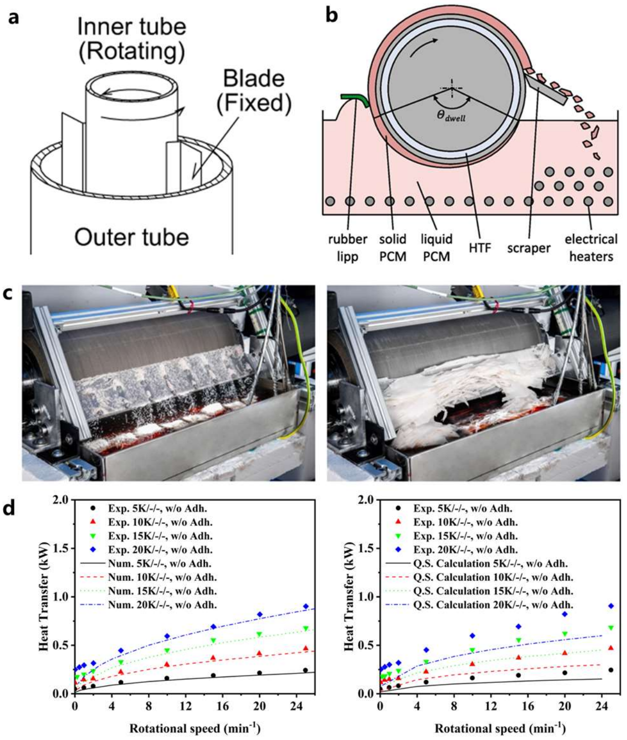

Figure 8. **(a)** Rotating heat transfer tube with fixed blades in convectional heat exchanger [61]; **(b)** Rotating heat transfer tube with fixed scraper in LTES system [66]; **(c)** Scraped solid PCMs at rotation speed of 6 rpm (left) and 12 rpm (right) [65]; **(d)** Comparison of numerical simulation data (left) and quasi-stationary calculation data (right) against experimental data [66].

Table 2 presents the summary of heat transfer enhancement by the rotation of a heat transfer tube in LTES systems. Overall, a few studies focused on this topic and explored the feasibility via experiments and simulations. The rotation of a heat transfer tube without a scraper proved to have slight effects on the charging performance at a low rotation speed. A higher rotation speed of the heat transfer tube needs to be further investigated, but such speed results in the consumption of larger parasitic power. In contrast, the rotation of a heat transfer tube with scrapers has been demonstrated to show good feasibility and significant effects on the discharging performance of LTES systems, since the scrapers can scrape the solidified PCM on the surface of the heat transfer tube and enhance the heat transfer coefficient of the heat transfer process between the liquid PCM and heat transfer tube. To achieve better heat transfer enhancement effects, efforts should be put into the design of heat transfer tubes and scrapers and the optimization of rotating parameters based on the operating conditions of shell-and-tube LTES systems.

Table 2. Summary of heat transfer enhancement by rotation of heat transfer tube in LTES system.

Heat transfer enhancement method	Parameter	Method	Process	Ref.
Tube rotation without scraping	Rotation speed, rotation direction	Experiment	Charging	[62]
Tube rotation without scraping	Rotation speed	Simulation	Charging	[63]
Tube rotation with scraping	Rotation speed	Experiment	Discharging	[64]
Tube rotation with scraping	Rotation speed	Experiment	Discharging	[65]
Tube rotation with scraping	Rotation speed	Simulation	Discharging	[66]
Tube rotation with scraping	Rotation speed	Simulation	Discharging	[67]
Tube rotation with scraping	Rotation speed	Simulation/experiment	Discharging	[68]

3.3. Flipping entire LTES system

The charging process of shell-and-tube LTES systems presents a nonuniform distribution at the upper and lower parts due to the existence of natural convection in liquid PCMs. Enhancing the charging process of the lower part of an LTES system and enhancing the overall charging rate by properly utilizing natural convection are important topics, since natural convection dominates the charging process of an LTES system when enough liquid PCM exists. Actually, the intensity and evolution of natural convection in a liquid PCM is influenced by the orientation of the LTES system [69], and thus some studies have explored flipping or changing the orientation of LTES systems to enhance the heat transfer rate. While the continuous rotation of an LTES system may consume more parasitic power, flipping the LTES timely to induce natural convection in the behindhand area of the LTES system has the potential to achieve an overall high heat transfer performance [40]. Therefore, researchers have explored the effects of step-by-step rotation and direct flipping of LTES systems, aiming to simplify continuous rotation and achieve a high heat transfer enhancement performance.

Jaberi and Hossainpour [70] investigated the effects of step-by-step rotation on the charging performance in a shell-and-tube LTES system, and various angles between each step, which were 90°, 120° and 180°, were considered. It was found that the LTES system with the rotation angle of 180° at each rotation step achieved the lowest melting time compared with those of other cases, since the lower half of the LTES system melted slower than the upper half and it had more opportunity to be rotated to the upper location via the 180° flipping, where natural convection was more intensive for enhancing the melting process. Similar phenomena were observed in a finned-tube LTES system by using step-by-step rotation, but the optimal rotation angle at each rotation step was affected by the number of fins [71]. In detail, the optimal layouts of a finned-tube LTES system were found to be four fins with a rotation angle of 90° or two vertical fins with a rotation angle of 180° (i.e., flipping). Overall, direct flipping of an LTES system can rotate its lower part, with a slower melting rate of the PCM, to the upper part, hence achieving a higher melting rate due to more intensive natural convection [40].

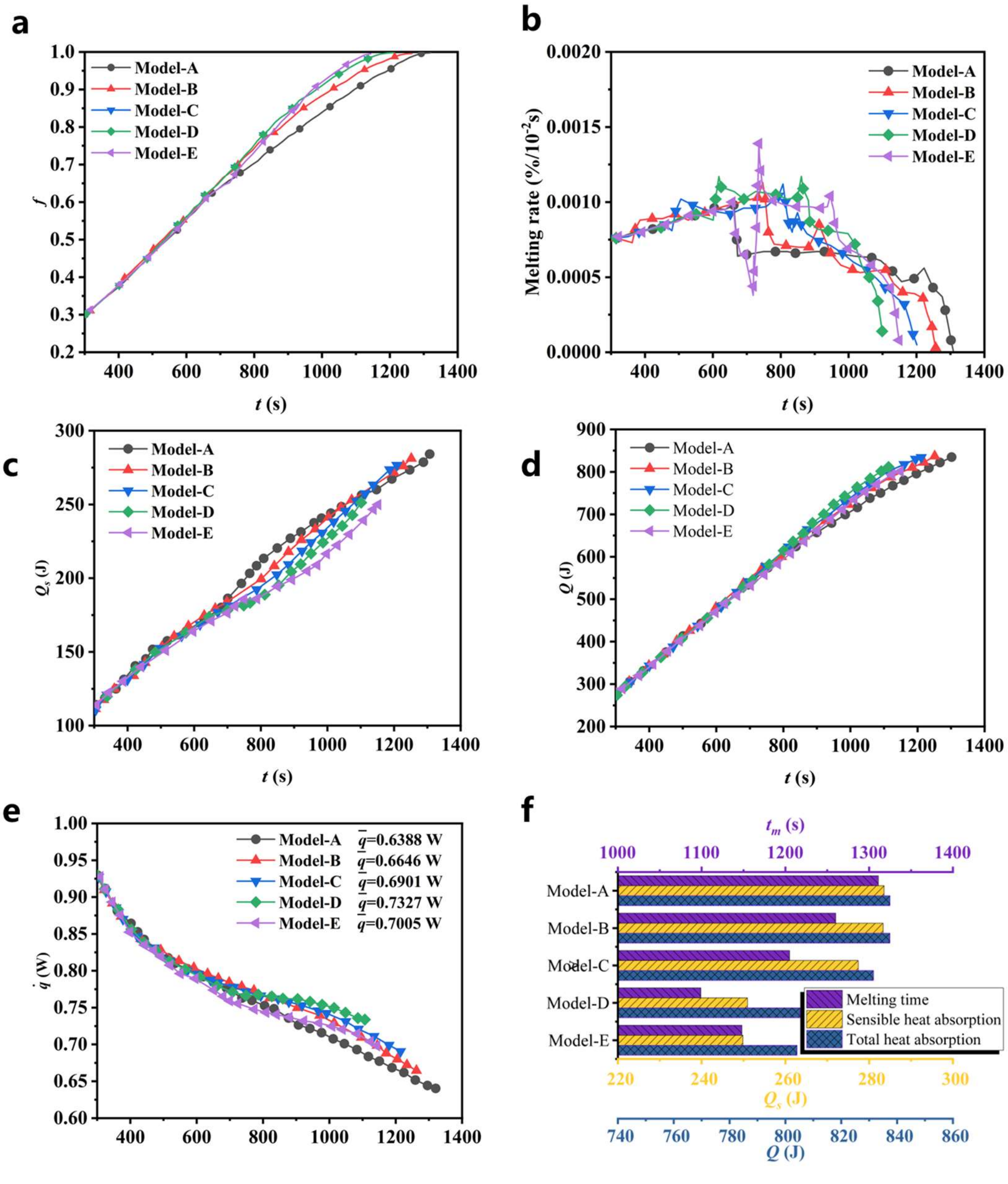

Figure 9. Specific effects of flipping time on melting properties in LTES system [74]: **(a)** evolution of liquid phase; **(b)** melting rate; **(c)** sensible heat energy absorption; **(d)** total heat energy absorption; **(e)** heat absorption rate comparison and **(f)** melting time and heat absorption.

In view of the demonstrated heat transfer enhancement effects of direct flipping, researchers have further investigated the effects of flipping in LTES systems from other aspects, aiming to obtain more guidelines for the design of rotating conditions. Dai et al. [72] evaluated the charging and discharging performances of a vertical shell-and-tube LTES system at various flipping times. The results highlighted that the total melting time presented a trend of first decreasing and then increasing with the increase in flipping time (dimensionless in unit), and the total melting time achieved the lowest value at flipping time of 0.5, which was 33.4% lower than that of an LTES system without flipping. The total solidification time showed a consistent overall trend with that of the total melting time, but the optimal value of flipping time was 0.25 due to the difference in the heat transfer mechanism between the charging and discharging processes. Huang et al. [73] studied the charging performance of a finned-tube LTES system at various flipping times, and Li et al. [74] investigated the charging performance of a triple-tube LTES system at various flipping times. Both highlighted the importance of flipping time to heat transfer enhancement effects, since the flipping of the entire LTES system could weaken hard-to-melt areas (especially at the lower part of the LTES system) and reduce the areas of high-temperature PCM during the melting process, thus improving the melting uniformity of the whole LTES system. For example, the charging performance of an LTES system at various flipping times is presented in **Figure 9**. For the Model A, there is no flipping. The flipping time of Model B, C, D and E is 360, 480, 600 and 720 s respectively. The charging rate increased by 14.7% and the total melting time was reduced by 16.7% when flipping time was 0.458 [74]. It should be noted that only one flipping was employed in this study, and so flipping time also deserves further study for better heat transfer enhancement effects.

Similar to the continuous rotation mode, the flipping mode has also been combined with other passive heat transfer enhancement methods, such as using eccentric heat transfer tubes [75,76]. The reviewed studies have demonstrated the efficacy of flipping on the charging and discharging performances of LTES systems with eccentric heat transfer tubes, which indicated an optimal eccentricity value for achieving the best heat transfer enhancement effects. **Table 3** shows the summary of heat transfer enhancement by the direct flipping of the entire LTES system. The flipping mode was employed for tube, finned-tube, triple-tube and eccentric-tube LTES systems, where various degrees of heat transfer enhancement effects were demonstrated. However, most of the studies explored the effects of flipping LTES systems from the aspect of the overall performances of the charging and discharging processes, and hence more efforts should be put into revealing the effects of flipping on the formation and evolution of natural convection in hard-to-melt areas. In addition, the flipping time of an LTES system is critical to achieving the best heat transfer enhancement effects, and optimal flipping times are different for the charging and discharging processes. Actually, the optimal flipping time is related to the liquid volume fraction in hard-to-melt areas and the relationship needs to be clarified for better implementation of the flipping mode. Also, all of the reviewed studies conducted simulations, there is a lack of experimental demonstrations of the flipping mode.

Table 3. Summary of heat transfer enhancement by direct flipping of entire LTES.

Heat transfer enhancement method	Parameter	Method	Process	Ref.
Tube, step-by-step rotation	Rotation angle	Simulation	Charging	[70]
Finned tube, step-by-step rotation	Rotation angle	Simulation	Charging	[71]
Tube, flipping	Flipping time	Simulation	Charging	[40]
Tube, flipping	Flipping time	Simulation	Charging, discharging	[72]
Finned tube, flipping	Flipping time	Simulation	Charging	[73]
Triple tube, flipping	Flipping time	Simulation	Charging	[74]
Eccentric tube, flipping	Eccentricity	Simulation	Charging, discharging	[75]
Eccentric tube, flipping	Eccentricity, rotation angle	Simulation	Charging	[76]

4. Conclusion

Rotation-based methods have emerged as active heat transfer enhancement methods and many achievements have been obtained by researchers around the world. This study conducted a short review of the mechanisms and applications of rotation-based heat transfer enhancement methods and the key conclusion is drawn as follows:

(1) Continuous rotation of whole LTES can achieve higher charging and discharging rates and a more uniform temperature distribution in shell-and-tube LTES systems, and the performance is affected by many critical parameters such as rotation speed and rotation duration. Rotation can also be combined with other passive heat transfer enhancement methods, such as using fins and metal foams. It is important to further reveal the heat transfer enhancement mechanisms of rotation, especially the coupling mechanisms with other passive heat transfer enchantment methods, which can help reduce the parasitic power and complexity of rotary device.

(2) The rotation of a heat transfer tube without a scraper proved to have slight effects on the charging performance at a low rotation speed, and the effects under higher rotation speed of the heat transfer tube needs to be further investigated. In contrast, the rotation of a heat transfer tube with scrapers has significant effects on the discharging performance of an LTES system, since the scrapers can scrape the solidified PCM on the surface of the heat transfer tube. More efforts should be put into the design of scrapers and the optimization of rotating parameters to achieve better heat transfer enhancement effects.

(3) Flipping can potentially work as a substitution for continuous rotation with lower parasitic power, and the performance is greatly affected by the flipping time, since the flipping time determines the utilization of natural convection, and the optimal flipping time is different for the charging and discharging processes. Most studies explored the effects of flipping LTES systems from the aspect of the overall performances of charging and discharging processes, ignoring the effects of flipping on the formation and evolution of natural convection in hard-to-melt areas. Actually, the optimal flipping time is related to the liquid volume fraction in hard-to-melt areas and the relationship needs to be clarified for better implementation of the flipping mode. Also, as all of the reviewed studies

conducted simulations, there is a lack of experimental demonstrations of the flipping mode.

(4) Although three rotation modes have been demonstrated to have considerable heat transfer enhancement effects, more efforts still need to be put into future designs and applications. On one hand, rotation has always been combined with other passive methods, such as using fins and metal foam, and so the composite effects on the heat transfer process, especially the evolution of natural convection, should be further revealed to provide guidelines for the optimization of parameters, such as rotation speed, rotation direction and flipping time. On the other hand, the application-oriented design of LTES systems with the rotation function is critically important for propelling the development of rotation-based heat transfer enhancement methods, which requires more experimental demonstrations in the research area, together with the consideration of economic performance. Subsequently, LTES systems with the rotation function can be considered in small-scale thermal energy storage scenarios, such as domestic and commercial applications.

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