The Effect of Geometric Parameters of a Container on Thermal Charging of Latent Heat Thermal Energy Storage System: A Review

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Abstract The latent heat thermal energy storage (LHTES) by phase change material (PCM) is more promising than supplementary technologies due to elevated heat capacity per unit volume and small volume change during heat exchange. The efficiency of the LHTES system mainly determines upon the thermophysical properties of PCM, operating conditions, and geometric parameters of a heat exchanger or PCM container. Geometric parameters like shape, size, height, type, and orientation of heat exchanger have greatly influenced the heat convey rate in between heat convey fluid and PCM. The tube and shell-type heat exchangers are most widely studied and analyzed by the researchers. This review presents and summarizes the different types of PCM container/heat exchanger which are used in the case of PCM along with geometric heat transfer enhancement techniques like fins, heat pipes, and multiple tubes, etc. The main focus is on the melting behavior of PCM interior the containers/heat exchangers which is an important variable to magnify the thermal charging capabilities of the LHTES system.

Keywords PCM · Heat transfer enhancement · LHTES · PCM heat exchanger · PCM container

1 Introduction

Thermal energy can be accumulated in three methods, i.e., "sensible heat, latent heat, and thermochemical heat storage" [1–3]. In sensible heat storage, heat is accumulated by altering the temperature without phase transformation. But heat is accumulated by the transition of the phase of material in latent heat storage [3]. Heat is stored during material melting known as thermal charging. This heat is released during

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solidification considered as thermal discharging. Latent heat storage more fascinates in solid to liquid transition as compared to sensible heat storage. This is because it is demanded low volume and weight of material to accumulate a specified amount of energy due to the high heat of melting per unit volume [1, 2]. Moreover, it provides the heat at a nearly fixed temperature which depends upon the melting temperature of a material [3]. Heat convey rate in between heat transfer fluid (HTF) and PCM depends upon the thermophysical properties of PCM mainly thermal conductivity, thermal gradient (between HTF and PCM), operating conditions of the HTF, and geometric characteristics of heat exchanger (HX)/PCM container. The total time requires for the thermal charging of LHTES mainly depends upon the liquefaction rate of PCM. But due to the inadequate thermal conductivity of most PCM [3], the liquefaction rate of PCM is not adequate to minimize the total thermal charging time. Thermal conductivity enhancement of PCM by adding nanoparticle, etc., is one way to overcome this limitation. But it creates a further burden on the cost of LHTES. The second approach is a modification in the fusion mechanism inside the container to expedite the liquefaction rate of PCM. Initially, conduction is the governing mode of heat transport due to solid PCM. But, as sufficient melting occurs, the convection mode is going to be more pronounced due natural current of liquid which is set up by temperature stratification. The convection process in the liquid PCM accelerates heat transport in the remaining unmelt portion of PCM which diminishes the total fusion time of PCM. The geometric parameters of the container significantly influence the thermal charging of PCM. Heat transport mechanisms, heat convey rate, and movement of solid–liquid front movement, temperature gradient inside PCM, and aggregate melting time are greatly impacted by the geometric characteristics of HX/PCM container.

2   Classification of PCM-Based LHTES System HX/container

In this review, the melting mechanism of PCM, the melting gradient of PCM, solid–liquid front movement, and the developed natural convection within PCM are discussed and summarized that contained in the different type of the geometry of the container. These shapes of HX mainly include spherical, rectangular, shell, and tube type containers and cylindrical (both horizontal and vertical) as shown in Fig. 1. The researchers found that geometric parameters like container shape, container height, width, the orientation of container, interior tube diameter, and shape, quantity, and shape of thermal conductivity enhancers like fins and heat pipes are deciding factor for total thermal charging time and heat transport rate.

2.1 Thermal Charging in a Spherical Vessel as LHTES System

Researchers mainly analyzed the melting of PCM inside the sphere by considering constraint and unconstraint mechanism. Spherical containers give the advantage of easy accumulation of PCM during packing and low volume to heat transfer ratio [4]. Tan [4] experimentally probed the melting mechanism and performed the comparative study of constraint and unconstraint melting by submerging the sphere in a hot bath. In the early stage, conduction was the governing mode of heat transfer. After melting, buoyancy-controlled convection was dominant in the PCM, and the heat transport rate was enhanced. In unconstraint melting, the unmelt portion was submerged at the base of the vessel due to the larger density than that of liquid PCM. Conduction through vessel was mode of heat transport in the submerged solid PCM at the base. But in the upper half, natural convection was governed the heat transport mechanism.

Two natural convection cells were developed in the upper half which is symmetric about the vertical axis. But in the constraint melting, solid PCM was suspended in the core of the sphere by hanging around the tube. Melting of PCM was all around the hanging solid PCM by natural convection mainly. Waviness was formed at the base of hanging solid PCM due to three natural convection cells. The liquefaction rate of PCM is more in the unconstrained melting due to the direct conduction from the bottom sphere surface to the submerged solid PCM. Sattari et al. [1] probed the liquefaction characteristics of PCM in the spherical capsule by CFD simulation. They found that waviness is formed in the bottom portion of capsules due to the unstable liquid of PCM. It concluded that 27% enhancement of diameters imparts to the 80% intensification of the liquefaction time of PCM. Li et al. [5] probed the constrained liquefaction of PCM inside the spherical vessel. It concluded that a
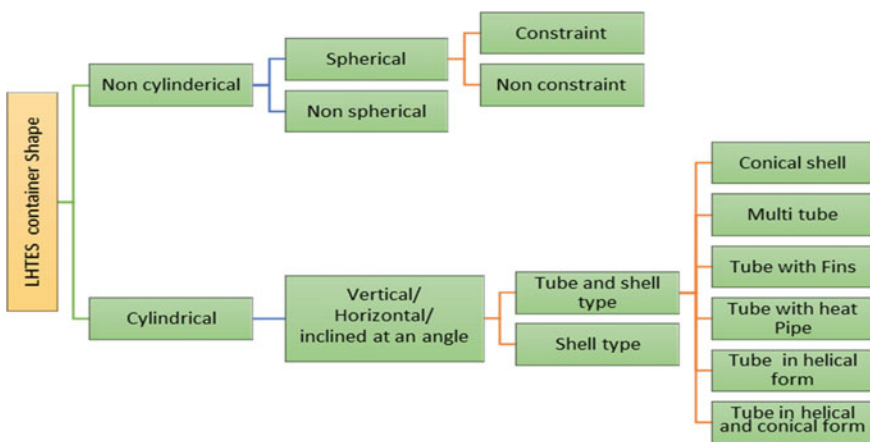

Fig. 1 Classification-PCM embedded HX container [1, 5–15, 19–28]

smaller radius sphere demonstrated the high melting rate of PCM. A high thermal conductive material is recommended for the spherical vessel to decrease the thermal charging time. It is advantageous to use a greater number of spheres of a smaller radius instead of a smaller number of spheres of larger radius.

2.2 Thermal Charging in a Non-cylindrical and Non-spherical Vessel as LHTES

Kamkari et al. [6] probed experimentally the fusion behavior of PCM material in the rectangular container with 90°, 45°, and 0° inclination angle with a horizontal plane. They provided the heat source on the right wall of the container. They probed that reducing the height of a container is beneficial for diminishing the total melting time in 90° and 45° inclination of the container. But there was no significant change in the horizontal configuration. It revealed that 0° and 45° inclined container had taken 53% and 35% less melting time compared to the vertical container. Horizontally placed container demonstrated the least melting time for the PCM but it was occupying more space. Further, they [7] probed the impact of fins by placing in their only vertical configuration of a container as their earlier work. Initially, the conduction mode was dominated during heat transport until a thin layer of liquid PCM was developed near the wall of the container. At this time, the thickness of liquid PCM was uniform near the container wall height. As melting continues, the thickness of liquid PCM was more at the top of the container as compared to the bottom of the container. At this time, the buoyancy force was dominating the viscous forces. Liquid PCM moved upward with hot wall and cold liquid returned downward with a solid–liquid interface. Consequently, a circulating convection current was developed between the container wall and solid–liquid interface which further enhance the heat transport rate. The circulating convection current zone was divided into parts as the insertion of fins. The heat transport rate was more above the fin surface due to strong vortex motion in the liquid PCM near the fin surface. They stated that fins (three) were reduced the melting time by about 37% as compared to the unfinned container due to the magnification of the heat transport area. But fins also developed the obstruction in circulating convection current which diminishes the heat transport rate. As a result, there was a requirement of an optimal number of fins. Further, they found that the fins impact was more at the lower wall temperature. Haddad et al. [8] numerically probed the liquefaction characteristics of paraffin in the wavy (bottom surface) trapezoidal cavity which is heated from below It stated that the liquefaction duration in the flat surface is nearly 2.5 times quicker than that in the wavy surface at a temperature gradient of 50 °C.

2.3 Thermal Charging in the Cylindrical Container as LHTES System

Different orientation of the cylinder like horizontal, vertical, and inclined was studied by the researchers during thermal charging. Seddegh et al. [9] simulated and compared the liquefaction characteristics of PCM in the "vertical and horizontal shell and tube" LHTES system. It found that the convective heat convey mode is dominating in the upper half portion of the horizontal container during heat absorption in the PCM. Hence, the rate of liquefaction is inflated at the inceptive stage of the charging operation. But the liquefaction rate is going to decrease as the melting of the lower portion start due to the absence of the buoyancy effect. Vertical container shows the greater liquefaction rate of PCM in the lower portion than that of horizontal. The liquefaction rate is more uniform in the vertical container than that of horizontal. A horizontal container is recommended for part load application as a better melting rate of the upper portion. Recently, Mahdi et al. [10] numerically probed the effect of PCM location on the thermal capabilities in the concentric pipe by Ansys Fluent. PCM was settled in the annulus and inner tube in the first and second cases, respectively. PCM accumulation in the inner tube is diminished the melting time about 50% than that of other case. This is happened because convection is dominated in the larger portion in the case second (inner tube PCM packing), but it is mainly restricted in the top portion in the case first after initial melting. Bechiri et al. [11] presented a numerical analysis to probe the liquefaction of PCM partially occupied in a perpendicular cylindrical tube with a constant temperature wall surface. It stated that at the inception of liquefaction (initial four minutes), the height of PCM does not influence the fusion process because thermal energy is disseminated by conduction inside PCM. Subsequently, after four minutes, the liquefaction time intensifies as PCM container height increases. The natural convection fluctuation actuated by altering the tube diameter and exterior wall surface temperature impacts remarkably the liquefaction process. Saraswat et al. [12] probed the liquefaction process of "industrial-grade paraffin wax" [12] occupied in a semi-cylindrical vessel with a heating strips (heat pipe) attached axially along with the core of semi-cylinder. It was found that the integration of heat pipes with PCM assists to extent convey of heat in the PCM, and hence, a remarkable diminishes in the aggregate required liqufication time of PCM. Joybari et al. [13] experimentally investigated single and multiple (five) tube with PCM incorporated in the shell. It was revealed that the multitube HX exhibited better performance than the single tube HX in terms of fusion duration and energy storage capacity due to extended heat convey surface area.

2.4 Thermal Charging in the Shell and Tube Model HX as LHTES System

Researchers probed the impact of a different configuration of the tube carrying HTF with PCM embedded in the shell-like single tube, multitube, coil form tube, and conical coil type, etc. In the research literature, nearly two-third studies of PCM embedded in the container is related to shell and tube container due to low heat loss in the cylindrical container than that of other [2]. Shell and tube diameter ratio "ꭓ" should be less than four to maximum the accumulated energy density [2]. But the "ꭓ" value should be 5.4 to optimize the total accumulated energy density and melting time. Hosseini et al. [14] probed the melting characteristics of material experimentally and numerically in tube and shell model in horizontal configurations. As time progress, natural convection is governed the heat transport in the liquid PCM. Sodhi et al. [15] numerically studied phase transformation attributes of PCM (Sodium Nitrate) in the horizontal conical vessel and tube type HX. They stated that 3.4° are the optimized angle of cone and 98.6 mm, 54 mm is the inlet and outlet optimized diameter of the conical vessel to reduce the charging duration for 96% portion melting. Fins increase the heat convey rate in conduction mode at the inlet portion of the conical shell, but they are insignificant at the outer portion of the conical shell. Recently, Al Siyabi et al.[16] analyzed charging and discharging characteristics of inclined (0°, 45°, 90°) tube and shell-type containers for PCM (Paraffin). 45° inclination angle was demonstrated the highest melting rate than that of the other two inclination. PCM melting gradient is dominated in the axial orientation than that of radial orientation in the inclination of 0°. But the liquefaction rate behavior is just the opposite in the inclination of 90°. The region which faces the buoyant force in convection mode has a remarkable influence on the melting rate. Mahdi et al. [17] experimentally examined the liquefaction characteristics of "paraffin wax in a conical coil" LHTES system in the cylindrical container. Their probes revealed that the liquefaction rate in the conical coil LHTES system is intensified by 22% in comparison with that of normal coil LHTES system due to the hike in the HTF pipe surface at the lower zone of a cylinder where the solid PCM subsided due to its relatively elevated density. Mao et al. [18] numerically probed heat convey characteristics during the melting of PCM in a "novel truncated cone shell and tube" LHTES vessel. It stated that aggregate liquefaction time diminishes nearly 30.69% compared with the traditional cylindrical vessel. Seddegh et al. [19] probed the thermal characteristics of the "conical and cylindrical" vessels. Their results showed that the conical vessel can accumulate thermal energy much quicker than the cylindrical vessel at the same working situation. Recently, Mahdi et al. [20] did a fascinating simulation and experiment by double pipe helical coil with PCM such that both the outer shell and interior tube are coiled. PCM is embedded in between the interior tube and shell. They revealed that melting time is diminished by about 25% and 67% for the same heat exchange surface area than that of straight horizontal and vertical HX. Melting is started from the top portion due to the buoyancy effect and move downward in all the cases. They gave the same result which verified by other researchers that after initial melting, the effect of convection

current is more in the top portion in the straight horizontal HX than that of straight vertical. But, in vertical HX, convection current is more dominating in the axial direction. The conduction mode of heat transport in bottom portion diminishes the heat transfer in the later stages. The innovative design took the advantage of both horizontal and vertical HX and reduced the limitations of the other two cases.

2.5 Impact on Thermal Charging by Insertion of Fins and Heat Pipe

Fins of high thermal conductive material are a cost-effective and efficient technique to increase the thermal charging rate [3]. Yang et al. [21] demonstrated that annular fins expedite the thermal capabilities of TES system. The fusion duration of PCM was diminished about 65% than that of without fins in their study by using annular fins. It stated that natural convection in PCM after melting is very pronounced to enhance the heat transport rate. Fusion time of PCM is decreased as number of fins increases up to a point after that it starts increases. The 0.0248 and 0.313 are optimal recommended value for ratio of thickness and gap between fins, ratio of gap between two fins, and length of tube, respectively. Mahood et al. [22] probed the consequences of fins positions on the liquifcation rate of PCM in the horizontal shell and tube type HX. When the fins are placed in the lower portion, below the horizontal axis (15° angle between fins) is most effective to decrease the melting time of PCM. This happened because all the fins directly improve the thermal conductivity in the region which has the lowest heat transport rate in the system. Diminishing the angle between the fins from 72° to 15° contribute to lower the fusion time of PCM. Karami et al. [3] probed the impact of perforated circular fins on LHTES capabilities of vertical shell and tube type HX. The total melting time slightly diminished about 7% than that of solid fins due to the expedition of buoyancy-driven convection flow by little impeding created through perforated circular fins. Bhagat et al. [23] probed the longitudinal fins geometric parameter incorporated with multiple tube in the PCM accommodated horizontally oriented shell by using Ansys Fluent. They accommodated the fins in both medium HTF and PCM. The main purpose of their research is to minimize the fluctuation in outlet HTF temperature for solar water heating. Fin's effectiveness is more in the case when fins accommodated in the both HTF and PCM than that of HTF. They recommended that thinner fins large in quantity is more advantageable than that of thicker fins small in quantity with constant volume of PCM. Nie et al. [24] numerically examined the impact of arrangement of longitudinal fins and other fins parameters in horizontally placed tube and shell model during successive thermal charging and discharging. They found an interesting result that total charging and discharging duration is diminished drastically by placing the fins uniformly in the container. On the contrary, the melting duration was reduced by accumulating all fins in the lower zone of the container but it showed a more adverse impact on the total solidification duration.

The heat pipe is a thermal device that enhanced the heat transport rate effectively in the LHTES system. The effective thermal conductivity of heat pipe is enormous than that of pure metals like copper, aluminum, etc. For Example, a heat pipe of copper with working fluid lithium can transfer the axial heat flux 10–20 kW/cm^2 at the temperature of 1500 °C [25]. Heat pipe can be assumed as a high thermal conductive rod during numerical simulation to minimize the numerical computational cost in place of evaporation and solidification model inside the heat pipe [26]. Mahdavi et al. [26] assumed heat pipe as a rod with effective thermal conductivity about 90 times of cooper thermal conductivity. Hence, the heat pipe is a suitable medium to encounter the limitation of LHTES system as low heat flux. Motahar et al. [27] placed a vertical heat pipe in a vertical shell containing PCM to expedite the heat transport rate from the heat source which is placed at the base of PCM shell. It stated that when the heat source temperature increased by 15 °C, then the melting time decreases by 53% by the heat pipe than that of the tube. Sharif et al. [28] simulated the thermal performance of an energy storage vessel (vertical cylinder) with heat pipe as charging unit and compared the result with HTF tube in place of the heat pipe. The heat pipe is more effective in terms of the melting time of PCM than that of tube. The effectiveness of heat pipe is more pronounced with the enhancement of condenser length and diameter of heat pipe. Researchers recommended the heat pipe to enhance the liquefaction rate in LHTES system. Mahdavi et al. [26] numerically probed the impact of heat pipe on the thermal charging of PCM containing nanoparticle packed in the shell and tube type HX by Ansys Fluent. The shell was vertically oriented, and the heat pipe was horizontally placed in PCM considering the tube as heat source. Insertion of one, two, three, and four heat pipes reduced the melting time about 40%, 61.2%, 76%, and 83%, respectively. It showed that impact of heat pipe is not proportional pronounced as number of heat pipe increased.

2.6   Comparative Studies of Thermal Charging in Containers

The conical shell and tube system (horizontal orientation) reveal a better performance in terms of the thermal charging rate than that of the horizontal cylindrical shell and tube model by enhancing the convection mode [15]. Spherical container exhibits low volume to surface area ratio which increases the effective heat transport area than that of the non-spherical vessel. A spherical container is good for packing in LHTES bed system [5]. The orientation of the rectangular container is drastically affecting the charging rate of PCM LHTES system. Magnification of the height to width ratio of a rectangular container reveals the higher melting rate of PCM [29]. Researchers stated that natural convection in the PCM expedites the heat transport rate than that initial pure conduction [29]. Rectangular vessel for PCM storage demands the half of melting time than that of a spherical vessel for the same volume and heat convey area between the heat convey fluid and the vessel wall [30]. Zivkovic et al. recommended to use a rectangular vessel instead of a spherical vessel [30]. Vyshak et al. [31] stated that a cylindrical shell and tube model are required the least charging time for the

same energy accumulation than that of a rectangular and cylindrical vessel. In the shell and tube HX, the optimal shell to tube radius ratio was found to minimize the total duration of thermal energy accumulation and maximize thermal energy capacity by the Seddegh et al. [32]. It stated that the ratio is 5.4 in the above conditions. The number of tubes and their position in the shell has a markable impact on the fusion rate. The tube near bottom of horizontal shell could enhance the fusion rate of PCM [33]. Tube and shell-type HX is good for small and medium size applications due to high energy efficiency (more than 70%) [34]. The melting rate is going to decrease as container height is increased. Horizontal PCM container reveals a high melting rate and low charging time in all the type [34].

3   Conclusion

Shell and tube HX is the most studied HX for PCM LHTES system. Researches have successfully used the heat pipe, fins, multiple tubes, a conical tube, and a helical tube to expedite the heat convey rate between HTF and PCM. Heat pipe in the PCM is very effective to boost the heat convey rate than that of other methods due to high effective thermal conductivity. There are very limited comparative studies available which compare the performance and effectiveness of the different type of PCM container/HX. It is required to critical analysis and compared the melting gradient, melting time, solid–liquid front movement and mode of heat convey, etc., for different types of PCM container/HX to decide the most promising HX. Further, cost is also an important factor for small and medium size LHTES applications during commercialization. Researchers have successfully used nanoparticle to enhance the thermal charging rate of LHTES. But it creates a further burden on the cost of LHTES system. Hence, it is beneficial to optimize the geometric parameter to enhance the thermal charging rate and thermal capacity of LHTES. It is also found in some cases that the geometrics parameter which enhances the thermal charging performance have an adverse effect on the thermal discharging stage or freezing operation.

References

1. Sattari H, Mohebbi A et al (2017) CFD simulation of melting process of phase change materials (PCMs) in a spherical capsule. Int J Refrig 73:209–218
2. Kalapala L, Devanuri J (2019) Parametric investigation to assess the melt fraction and melting time for a latent heat storage material based vertical shell and tube heat exchanger. Sol Energy 193:360–371
3. Karami R, Kamkari B (2020) Experimental investigation of the effect of perforated fins on thermal performance enhancement of vertical shell and tube latent heat energy storage systems. Energy Convers Manage 210:112679
4. Tan F (2008) Constrained and unconstrained melting inside a sphere. Int Commun Heat Mass Transfer 35:466–475

5. Li W, Li S et al (2017) Numerical study on melt fraction during melting of phase change material inside a sphere. Int J Hydrogen Energy 42:18232–18239

6. Kamkari B, Shokouhmand H (2014) Experimental investigation of the effect of inclination angle on convection-driven melting of phase change material in a rectangular enclosure. Int J Heat Mass Transf 72:186–200

7. Kamkari B, Shokouhmand H (2014) Experimental investigation of phase change material melting in rectangular enclosures with horizontal partial fins. Int J Heat Mass Transf 78:839–851

8. Haddad Z, Iachachene F (2019) Melting characteristics of organic phase change material in a wavy trapezoidal cavity. J Mol Liquids, 112132

9. Seddegh S, Wang X et al (2016) A comparative study of thermal behaviour of a horizontal and vertical shell-and-tube energy storage using phase change materials. Appl Therm Eng 93:348–358

10. Mahdi M, Mahood H et al (2019) Numerical study on the effect of the location of the phase change material in a concentric double pipe latent heat thermal energy storage unit. Thermal Sci Eng Progr 11:40–49

11. Bechiri M, Mansouri K et al (2019) Study of heat and fluid flow during melting of PCM inside vertical cylindrical tube. Int J Therm Sci 135:235–246

12. Saraswat A, Bhattacharjee R et al (2017) Investigation of diffusional transport of heat and its enhancement. Appl Therm Eng 111:1611–1621

13. Joybari M, Seddegh S et al (2019) Experimental investigation of multiple tube heat transfer enhancement in a vertical cylindrical latent heat thermal energy storage system. Renew Energy 140:234–244

14. Hosseini M, Rahimi M et al (2014) Experimental and computational evolution of a shell and tube heat exchanger as a PCM thermal storage system. Int Commun Heat Mass Transfer 50:128–136

15. Sodhi G, Jaiswal A et al (2019) Investigation of charging and discharging characteristics of a horizontal conical shell and tube latent thermal energy storage device. Energy Convers Manage 188:381–397

16. Al I, Khanna S et al (2019) An experimental and numerical study on the effect of inclination angle of phase change materials thermal energy storage system. J Energy Storage 23:57–68

17. Mahdi Mustafa S, Mahood Hameed B et al (2019) Experimental study on the melting behavior of a phase change material in a conical coil latent heat thermal energy storage unit. Appl Therm Eng 11:40–49

18. Mao Q, Liu N et al (2019) A novel shell-and-tube thermal energy storage tank: Modeling and investigations of thermal performance. Appl Therm Eng 159:113964

19. Seddegh S, Cao F et al (2017) Comparison of heat transfer between cylindrical and conical vertical shell-and-tube LHTES systems. Appl Therm Eng

20. Mahdi M, Mahdi J et al (2020) Improved PCM melting in a thermal energy storage system of double-pipe helical-coil tube. Energy Convers Manage 203:112238

21. Yang X, Lu Z et al (2017) Thermal performance of a shell-and-tube latent heat thermal energy storage unit: Role of annular fins. Appl Energy 202:558–570

22. Mahood H, Mahdi M et al (2020) Numerical investigation on the effect of fin design on the melting of phase change material in a horizontal shell and tube thermal energy storage. J Energy Storage 29:101331

23. Bhagat K, Prabhakar M et al (2018) Estimation of thermal performance and design optimization of finned multitube latent heat thermal energy storage. J Energy Storage 19:135–144

24. Nie C, Deng S et al (2020) Numerical investigation of PCM in a TES unit with fins: consecutive charging and discharging. J Energy Storage 29:101319

25. Reay D, Kew P et al (2013) Heat pipes: theory, design and applications. Butterworth Heinemann

26. Mahdavi M, Tiari S et al (2020) A numerical study on the combined effect of dispersed nanoparticles and embedded heat pipes on melting and solidification of a shell and tube latent heat thermal energy storage system. J Energy Storage 27:101086

27. Motahar S, Khodabandeh R et al (2016) Experimental study on the melting and solidification of a phase change material enhanced by heat pipe. Int Commun Heat Mass Transfer 73:1–6

28. Sharifi N, Wang S et al (2012) Heat pipe-assisted melting of a phase change material. Int J Heat Mass Transf 55:3458–3469
29. Fadl M, Eames P (2019) A comparative study of the effect of varying wall heat flux on melting characteristics of phase change material RT44HC in rectangular test cells. Int J Heat Mass Transf 141:731–747
30. Zivkovic B, Fujii I (2001) Analysis of isothermal phase change of phase change material within rectangular and cylindrical containers. Sol Energy 70:51–61
31. Vyshak N, Jilani G (2007) Numerical analysis of latent heat thermal energy storage system. Energy Convers Manage 48:2161–2168
32. Seddegh S, Wang X (2017) Investigation of the effect of geometric and operating parameters on thermal behavior of vertical shell-and-tube latent heat energy storage systems. Energy 137:69–82
33. Esapour M, Hosseini M (2016) Numerical study on geometrical specifications and operational parameters of multi-tube heat storage systems. Appl Therm Eng 109:351–363
34. Zayed M, Zhao J et al (2020) Recent progress in phase change materials storage containers: geometries, design considerations and heat transfer improvement methods. J Energy Storage 30:101341