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Numerical Investigation of the Impact of Toothed Fins on the Heat Transfer Performance of a Shell-and-Tube Exchanger during Phase Change Material Melting Process

Abstract:

The poor thermal conductivity of phase transition materials hampers the development of latent heat energy storage devices. There is much scholarly interest in enhancing heat transmission in these materials. Using a finned shell-and-tube exchanger is a traditional strategy for improving the effectiveness of latent thermal energy storage devices. However, the storage systems' actual working volume decreases when many fins are added. Numerous studies have shown that toothed fins are more efficient in transferring heat than regular fins. As a result, it is anticipated that toothed fin latent heat energy storage systems will produce better thermal effects. Unfortunately, the impact of toothed fins on the melting of phase transition materials has only been briefly discussed in published literature. To close this important knowledge gap, this paper thoroughly studies two regularly used fins, namely the annular fin and longitudinal fin with toothed apertures. The impact of different toothed-opening volumes and tooth spacing on the melting process of phase transition materials are examined using numerical simulations. The results show that toothed fins have a 20% lower fin volume than traditional circular and longitudinal fins, which has a marginally less positive impact on phase change material melting times of 1.09% and 0.98%, respectively. The recommended toothed-opening volume and tooth count for the annular fin are 10%–20% and 16 teeth, respectively, whereas the recommended toothed-opening volume and tooth spacing for the longitudinal fin are 10%–20% and 1mm, respectively. Additionally, the tooth spacing affects heat transfer, in one investigation, decreasing the tooth spacing by 2.5 and 2 times led to reductions in the melting periods of phase change materials of 60 and 70 seconds, respectively.

Keywords: latent heat energy storage systems; phase change materials; Toothed fin; Heat transfer, Melting process analysis

Nomenclature		Greek symbols	
Cp	specific heat capacity (kJ/kg·K)	β	expansion coefficient (K^{-1})
d	space of teeth	λ	thermal conductivity (w/(m·K))
g	gravity (m/s^2)	μ	dynamic viscosity (Pa.s)
S	number of teeth	ρ	density (kg/m3)
T	temperature (K)		
$T_{solidus}$	temperature of solid PCM (K)		
$T_{liquidus}$	temperature of liquid PCM (K)		

t	time (s)	Abbreviation	
t_{nofin}	total melting time of PCM of bare tube (s)	LHTS	latent heat thermal storage
$t_{toothed\text{-}fin}$	total melting time of PCM of toothed fin (s)	PCM	phase change material
$t_{ordinary\text{-}fin}$	total melting time of PCM of ordinary fin (s)	HTF	heat transfer fluid
L	liquid fraction		
N	heat transfer enhancement of fin on PCM		
Nu	nusselt number		
v	velocity magnitude (m/s)		

1. Introduction.

Cars, factories, infrastructure and other industrial projects consume large amounts of fossil fuels. The greenhouse gases released by fossil fuels cause global warming, significantly affecting our environment. The increase in greenhouse gas emissions and the rapid depletion of fossil fuels have aroused many researchers' interest in renewable energy sources [1, 2]. However, most renewable energy sources face the problem of space-time mismatch between the production and consumption sides, which significantly restricts the development of renewable energy technology [3, 4]. The International Energy Association (IEA) reported in 2014 [5] that only about 69 percent of the primary energy supply reaches final consumption, while about 31 percent of direct energy is wasted during fuel conversion. To develop renewable energy technologies and improve the utilization rate of non-renewable energy, energy storage technology is an important research topic because it can make the energy system more efficient.

Thermal energy storage system (TES) provides the possibility of storing a large amount of heat energy, especially latent thermal energy storage (LHTES) system can complete the storage and release of energy within a relatively small range of temperature change [2, 6]. However, most phase change materials (PCM) have a thermal conductivity of (0.2-0.4 $W.m^{-1}.K^{-1}$) [7], and such a low thermal conductivity prevents PCM from achieving its optimal heat storage capacity. Therefore, using different techniques to improve the thermal performance of PCM in LHTES systems has attracted extensive attention from researchers [8, 9]. These methods for enhancing the heat performance of the LHTES system can be divided into three categories [10] :(1) improving the thermal conductivity of the PCM by adding nanoparticles or graphite with high thermal conductivity to the PCM; (2) expanding the heat transfer area of the PCM by using structures such as fins; and (3) expanding the heat transfer temperature range of the HTF by using PCM with different phase transition temperatures. Vertical or horizontal shell and tube heat exchangers are generally used in current LHTES [11].

Homogeneous mixing of nanoparticles with high thermal conductivity can improve the thermal conductivity of the liquid, which is the production method of nanofluid[12]. Nanofluids are widely used to enhance the heat transfer of various materials. Similarly, adding nanoparticles to PCM can be an essential method to improve its thermal conductivity. Bondareva et al. [13] studied the heat transfer enhancement of PCM by adding nanoparticles into a cavity with fins. Their simulation results show that nanoparticles can enhance heat transfer in PCM; a large inclination Angle can also improve PCM's melting speed. Khodadadi and Hosseinizadeh [14] demonstrated the effect of nanoparticle dispersion in PCM to improve latent heat storage. These types of PCM are known as nanoparticle-enhanced phase change materials (NEPCM).Yang et al. [15] experimentally studied the influence of tilt Angle on the melting time of PCMs in inclined cavities. The chamber was filled with metal foam during the experiment to enhance heat transfer. The results show that Compared with 90 degrees, the full melting time at 0 degrees, 30 degrees and 60 degrees is reduced by 12.28%, 22.81% and 34.21%, respectively. Afsharpanahet al.[16] used numerical simulation to study the composite enhanced heat transfer of a cylindrical device with a double helix spiral cooling tube by using connecting plates and nano-additives to enhance heat transfer. The results show that the solidification rate can be increased by 29.9% when the nano-additive is combined with the connecting plate. Afsharpanah et al.[17] studied the influence of porous foams, fins, and nanomaterials on the solidification process of PCM. Their study found that using copper foam, which accounts for 3% of the container volume, can reduce the solidification time by 84.6%, and using copper foam and nano copper oxide can reduce the solidification time by 92.5%. Xiao and Zhang. [18] It was reported that when the parwax-EG (expanded graphite) was used as the energy storage medium in a vertically placed shell-and-tube heat exchanger, the melting time was reduced by 40.6% compared to paraffin alone. Similarly, Das et al. [19] studied the melting phenomenon of a single vertical tube shell latent heat storage device, and they found that the thermal conductivity of PCM significantly reduced the melting time due to the enhanced encapsulation of the graphene nanosheets. When the graphene content is 2 vol%, the melting time is significantly reduced by 41% when the high temperature is 60 ° C, and by 37% when the high temperature is 70 ° C. To make a long story short ,the use of nanomaterials or metal foam can improve the thermal conductivity of PCM, but this method will reduce the energy storage capacity of PCM and the cost is relatively high[20]. For more research on PCMs micro/nano enhancement techniques, please refer to reference [21].

Among the numerous heat transfer enhancement methods, using fins to expand the heat transfer area of PCM is very popular due to its low cost, availability, and effectiveness. Furthermore, comparative studies using fins or foams [22] and fins or nanoparticles [23] confirm that fins embedded in PCM can accelerate the charging/discharging process of LHTES systems more effectively than using foam or adding nanoparticles.

Kalhori and Ramadhyani et al.[24] experimentally studied the influence of longitudinal fins on the melting process of PCM in vertically placed LHTES for the first time and concluded that longitudinal fins could improve the melting rate of PCM. Rathod and Banerjee et al. [25] experimentally investigated the difference in charge/discharge time of PCM in LHTES with three fins placed horizontally. The experimental results show that the increase of HTF inlet temperature is more sensitive to the increase of heat transfer than the increase of HTF mass flow rate. It has been observed that the installation of three fins can reduce the setting time by 43.6%. Ismail et al.[26] experimentally studied the effects of different numbers, thicknesses and lengths of fins on the melting time of PCM. The results show that the number, thickness, and length of fins can improve the melting rate of PCM, but this also leads to a decrease in the storage capacity of the PCM. Afsharpanah, F et al. [27] numerically investigated the effect of the simultaneous use of plate fins and various types of carbon-based nanomaterials (NMs) on the melting process of PCM. The influences of fin network, nanoparticle type, volume, and mass concentration on PCM's melting process were investigated using the control variable method. The results show that MWCNT particles present a 2.77% and 17.72% faster freezing rate at identical NM volume and mass fractions than the CuO particles. The combination of plate-fin network and MWCNT particles is a promising technique that can expedite the ice formation rate by up to 70.14%. Soltani et al. [28] numerically investigated the use of fins and rotating machinery together to enhance heat transfer in PCM. The results show that the melting time of PCM is reduced by 83.21% under the action of rotating fin. The heat transfer intensity increased by 12.89W. In addition, the speed also has a great influence on the heat transfer of PCM. When the rate is increased from 0.1rpm to 1rpm, the melting and solidification time of PCM are increased by 2.45 times and 3.87 times, respectively. Afsharpanah et al. [29] numerically simulated the charging process. of a small-scale cuboid-shaped ice container unit with two rows of serpentine tubes equipped with connecting plates. They conducted a quantitative study of the effects of various dimensionless parameters on the flow and geometry of the convoluted tubes and extended surfaces. The results show that the average energy charging rate can be increased by 18% by using a full-covered thick plate. Masoumpour-Samakoush et al. [30] proposed inserting innovative fins, a combination of rectangular and triangular fins. Their work studied the effects of the fin structure, triangle fin height and hot wall temperature on the melting process of PCM. The results show that the proposed shape can increase the melting rate by about 57.56%. Increasing fin height, fin number and hot wall temperature can shorten the melting time of PCM. Tao and He [31] numerically studied the effect of fins on the melting characteristics of PCM in horizontally placed LHTES. Their numerical results show that any method of increasing the fin volume will reduce the volume of effective PCM and thus reduce the heat storage capacity of LHTES, the following fin parameters are recommended: fin number 7; dimensionless fin thickness 0.1; dimensionless fin height, 0.8.

In addition, some researchers carried out two-dimensional topology optimization of fins and proposed longitudinal fins with different shapes, further improving the charge/discharge rate of the LHTES system. Sciacovelli, A. et al. [32] numerically studied the effect of "Y-shaped" fins on the heat transfer enhancement of PCM. The results showed that compared with longitudinal fins, "Y-shaped" fins at the optimal angle could shorten the melting time of PCM by 24%. In addition, they also found that large-angle "Y-shaped" fins have a better effect on heat transfer enhancement in the first half of the melting process, and a small angle has a better impact in the later part of the melting process. In addition to the Y-fin, there are many new fins, such as the "dendritic" fin [33], "spider" fin [34], "T-shaped" fin [35], "Y-shaped" fin [36], "anchor-type longitudinal fin" [37], etc. The structural innovations of these new fins are mainly focused on the two-dimensional level, especially on the longitudinal fin cross-section shape, and the principle of heat transfer enhancement is to increase the heat transfer area between PCM and fin [38].

Some scholars have studied the influence of different fins on the heat transfer of PCM from three-dimensional aspects. Zhang, Shengqi et al. [39] numerically studied the effects of longitudinal fins, annular fins, spiral fins and quadruple spiral fins on the melting process of PCM in LHTES. The results show that the thermal impact of fins with the same structure differs in LHTES placed differently. They proposed double helix fins suitable for the vertical placement of LHTES; Quadruple spiral fins ideal for the horizontal placement of LHTES. The melting time of PCM in vertical and horizontal LHTES with the most suitable fins is reduced by 31.0% and 10.0%, respectively. Zonouzi et al. [40] numerically studied the charging process of spiral-finned LHTES. The results show that for the helical finned LHTES, besides the axial velocity component, the molten PCM also has circumferential and tangential velocity components, which is conducive to the deep penetration of the melt front. Therefore, the spiral-finned LHTES system will have transverse and longitudinal convections. In addition, they found that in spiral fin HTES, the total melting time of PCM was reduced by 18.25%, 21.5% and 16.75%, respectively, when the inner tube wall temperatures were 345, 355 and 365 K, respectively.

Based on the above literature survey, fin use can significantly enhance the heat transfer of LHTES, but excessive use of fins will reduce the effective volume of PCM [13] and impedes the natural convection [10]. Many scholars have pointed out that toothed fins can improve fluid heat transfer [36-38] and are conducive to generating convection. However, few studies have investigated the heat transfer performance of the toothed fins in LHTES. To reduce the volume of the fin, improve the heat transfer efficiency and fill the research gap in the application of toothed fins in LHTES, two most classic fin, the annular fin and longitudinal fin [10] with toothed opening, are investigated comprehensively for the first time in this study. Most studies on the design of toothed fins are around the number of teeth and tooth spacing; this study is no exception. Because the toothed-opening volume directly affects the surface area of the fin and the effective working volume of LHTES, we first study the tooth-opening volume of the fin. The results confirm the excellent performance of toothed fins in LHTES, reveal the effect of toothed fins on PCM's melting process, and find the optimum toothed-opening volume range of the annular fin and longitudinal fin. In addition, we also studied the effect of tooth spacing on the melting of PCM. The results show that the reduction of tooth spacing benefits the heat transfer of PCM under the same opening volume. In two cases in this study, the tooth spacing was reduced by 2.5 and 2 times, and the melting time of PCM was reduced by 60s and 70s, respectively. This study provides a basis for applying toothed fins in LHTES.

2. Model description

2.1Physical model and boundary conditions

The physical models of the shell and tube LHTES considered in this study, including longitudinal fin, are used for horizontally placed LHTES, and annular fin are used for vertically placed LHTES (such fins and placement can be combined to achieve higher heat transfer performance [39]) are shown in Fig. 1. The size of the two heat exchangers is the same. However, the types of fins are different, and the initial condition for both models is that the temperature of the entire computation domain is 300K. The HTF (heat transfer fluid) flowing through the inner tube is water [39], the type of inlet is velocity inlet, the temperature is 360k and flow rate is 0.1m/s, and the kind of outlet is outflow [40]. The inner tube is made of copper with a diameter of 25mm and a thickness of 1mm [41]. The material of the fin integrated with the inner tube is also copper, with a thickness of 1mm. The height of the longitudinal fin is 10mm, and the height of the annular fin is 6.25mm [42]. The shell diameter is 50mm; this study ignored its thickness and set it as an adiabatic wall. PCM is filled between the shell and the inner tube. The thermophysical properties of PCM are shown in Table 1 [42]. The length of the entire LHTES system is 100mm.

For the horizontally placed LHTES, HTF flows from left to right; for the vertically placed LHTES, HTF flows from bottom to up (This direction of flow allows heat from HTF to be well absorbed by PCM [10]), and the flow rate is 0.1 m/s. The structure of the toothed fin in this study is shown in Fig. 2. For the longitudinal fin, remove a certain percentage of the fins evenly to give it a toothed shape, and the volume of the remaining fin is adjusted by controlling the tooth pitch and tooth number. For the annular fin, fan-shaped clipping was carried out along the symmetry axes established in the horizontal direction, and the volume of the remaining fin was controlled by the angle of the fan-shaped clipping area and the number of symmetrical axes. This study analyzed the influence of volume of 100% - 40% fin on the charging process of LHTES. Due to the similar geometric structures of different percentages of fin, only part of the toothed-fin model was shown in Fig. 1.

Table 1
The physical properties of the PCM **[42].**

Thermophysical property	Value
Range of melting temperature (K)	325-328
Density, ρ (solid phase) (kg/s)	900
Density, ρ (liquid phase) (kg/s)	773
Dynamic viscosity, μ (Pa·s)	0.03
Thermal expansion coefficient, β (k^{-1})	0.001
Thermal conductivity, λ (solid phase) (w/m·k)	0.28
Thermal conductivity, λ (liquid phase) (w/m·k)	0.14
Specific heat, *Cp* (solid phase) (kJ/kg·K)	2464
Specific heat, *Cp* (liquid phase) (kJ/kg·K)	2950
Latent heat, *ΔH* (J/kg)	205600

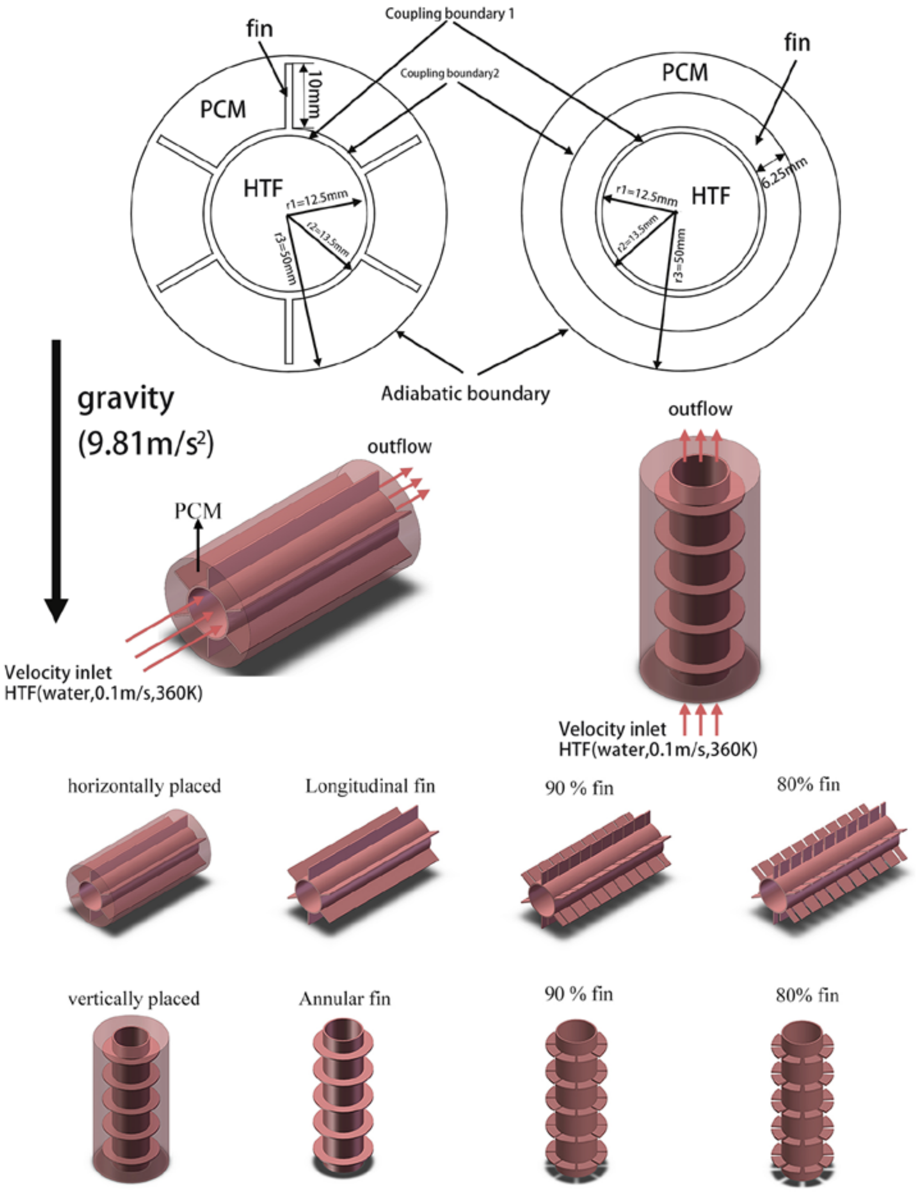
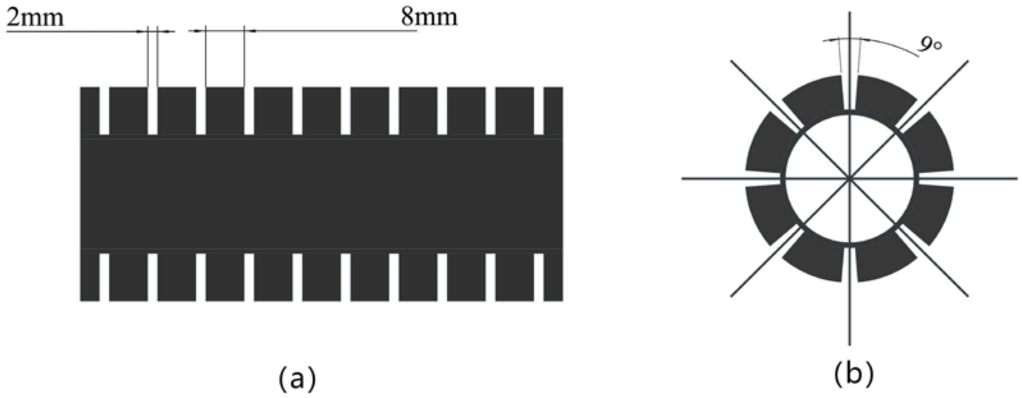


Fig .1 3D shell and tube heat exchanger model, boundary conditions and toothed-open fin in this study



(a)

(b)

Fig. 2 The structure of the toothed fin (80% fin), (a) Vertical section of longitudinal fin, (b) horizontal section of the annular fin.

Boussinesq assumption is often used to describe the natural convection of PCM in numerical simulation [43]. Similarly, in this study, the Boussinesq assumption was also adopted for the density value of PCM, which was 900 [44]. Due to the difference in *Cp* and λ of solid and liquid paraffin wax, *Cp* and λ were linearized when paraffin wax was in the melting temperature range. The linearization processing expression is as follows [42]:

$$c_p = \begin{cases} 2464 & T \le T_{solidus} \\ aT + b & T_{solidus} < T < T_{melting} \\ 2950 & T \ge T_{melting} \end{cases} \tag{1}$$

$$\lambda = \begin{cases} 0.28 & T \le T_{solidus} \\ cT + d & T_{solidus} < T < T_{\mathrm{melting}} \\ 0.14 & T \ge T_{\mathrm{melting}} \end{cases} \tag{2}$$

Where *T* is the current temperature of PCM, *a, b, c, and d* are constants.

2.2 Governing equations

The numerical model in this study is based on the following assumptions [44] : (1) The PCMs density variation is assumed following Boussinesq. (2) The flow of liquid PCM is incompressible laminar flow. (3) The shell of the heat exchanger is insulated. The essence of the solid-liquid interface problem in the melting process of PCM is the phase transition heat transfer problem, which is usually described by the enthalpy method [45] in standard numerical calculation software, and the governing equation is as follows [40]:

Continuity equation:

$$\nabla \cdot \vec{V} = 0 \tag{3}$$

Momentum equations:

$$\frac{\partial \vec{V}}{\partial t} + \vec{V} \cdot \nabla \vec{V} = \frac{1}{\rho}\left(-\nabla P + \mu \nabla^2 \vec{V} + \rho \vec{g} \beta \left(T - T_{ref}\right)\right) + \vec{S} \tag{4}$$

Energy equation:

$$\frac{\partial H}{\partial t} + \nabla \cdot (\vec{V}H) = \nabla \cdot \left(\frac{k}{\rho} \nabla T\right) \tag{5}$$

The equation on enthalpy:

$$H = h + \Delta H \tag{6}$$

$$h = h_{ref} + \int_{T_{ref}}^{T} CpdT \tag{7}$$

$$\Delta H = \lambda L \tag{8}$$

$$\lambda = \begin{cases} 0 & T \le T_{solidus} \\ \dfrac{T - T_s}{T_l - T_s} & T_{solidus} < T < T_{meting} \\ 1 & T \ge T_{meting} \end{cases} \tag{9}$$

Where h is the sensible heat enthalpy, $\triangle H$ is the latent heat enthalpy; T_{ref} is the reference temperature; λ is the liquid phase fraction; $L$is is the latent heat of PCM; T is the current temperature of PCM.

In the momentum equation, Eq. (4), for involving the effect of phase change in the convection heat transfer, $\vec{S}$ is added as the source term, which is called Darcy's law damping term, and it is defined as:

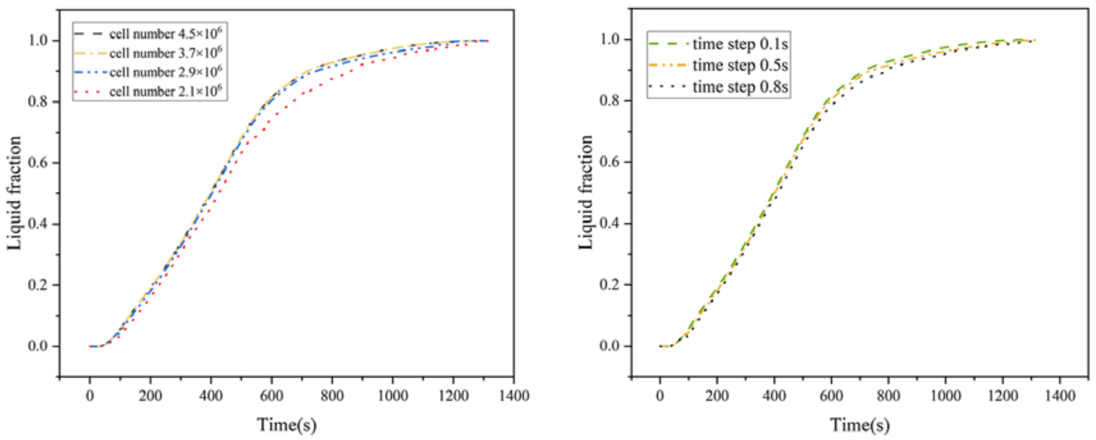
$$\vec{S} = \frac{(1-\lambda)^2}{\lambda^3 + \grave{o}} A_{mush} \vec{V} \tag{10}$$

Where ϵ is a constant less than 0.001 to avoid a denominator of 0; where A_{mush} is the mush zone factor, in most numerical studies, it is set to $10^5 - 10^6$ [46]; in this study, A_{mush} is assumed to be 10^6, because it gives the best results in this value [40].

3. model validation

3.1 mesh and time step independence study

The accuracy of numerical simulation results is closely related to the number of cells and time step, so verifying the mesh and time step independence is necessary. Fig. 3 shows the effect of different cell numbers and time steps on the liquid phase fraction during the melting of PCM. The number of cells in the three cases is 2.1×10^6, 2.9×10^6, 3.7×10^6 and 4.5×10^6 respectively. The time step is 0.1s,0.5 s and 0.8 s, respectively. It can be seen from Fig. 3(a) that the PCM melting liquid fraction corresponding to 3.7×10^6 and 4.5×10^6 is almost the same. To reduce the calculation amount of numerical simulation, a cell number of 3.7×10^6 is appropriate. Similarly, the numerical simulation results of the time step of 0.5s and 0.8 s are also almost similar, so the time step of this study is 0.5 s.



(a) (b)

Fig.3. (a) Mesh study, and (b) Time-step independence study of the current work.

3.2 Model validation

The accuracy of numerical simulations needs to be compared with the work of other researchers. Fig. 4 shows the difference between this study's numerical simulation results and Darzi et al.'s work [47]. As can be seen from the figure, there is a good agreement between this study and their conclusions. In addition, Martin L et al. [48] experimentally and numerically studied the effect of HTF inflow direction on PCM's solidification/melting time in a vertically placed shell-and-tube heat exchanger. In the experiment, they measured the temperature of a point in the heat exchanger by thermocouple. As shown in Fig. 5, the temperature prediction results of the numerical simulation at the point agree with their experimental results. The comparison results above illustrate the reliability of the numerical model in this study.

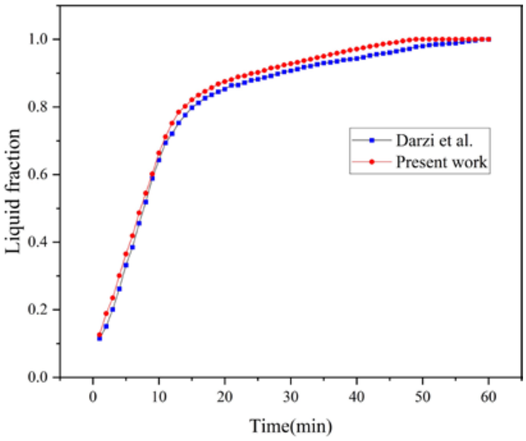
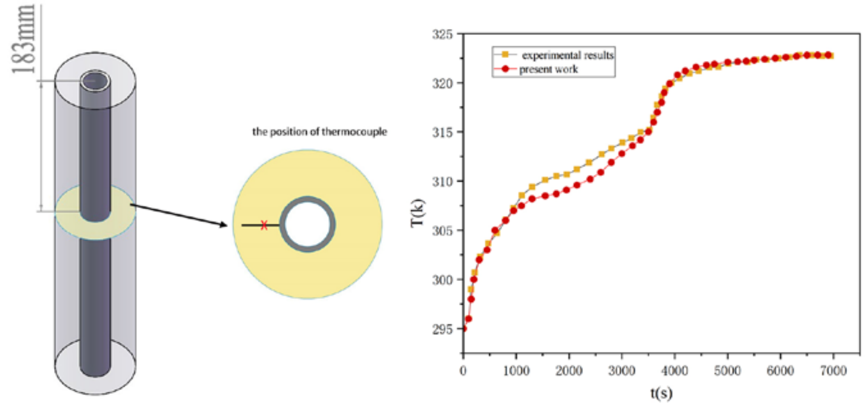


Fig.4. The comparison of liquid fraction between the simulation result of Darzi et al. [47]and the present work.



(a) (b)

Fig.5. The comparison of temperature between the experiment result of Martin L et al.[48] and present work. (a) The position of the thermocouple, (b) the Temperature curve of this study and the experiment result.

4. Results and discussions

4.1 Effect of different volumes of toothed fin on heat transfer in PCM

Because the toothed-opening volume directly affects the surface area of the fin and the effective working volume of LHTES, we first study the effect of tooth-opening volume on heat transfer in PCM. In this section, the annular fin was toothed-opening, and the impact of different opening volumes with eight teeth on the melting of PCM was studied. In addition, the longitudinal fin was toothed-opening, and the effect of varying opening volumes with ten teeth on the melting of PCM was studied.

4.1.1 Annular toothed fin

Fig. 6 shows the contours of PCM liquid fraction with different teeth opening volumes during the melting process of PCM. The inlet direction of HTF is opposite to the direction of gravity, from bottom to top, which is conducive to the heat transfer rate of HFT [49]. As can be seen from the tube and fin section in the figure, the temperature of the upper tube and fin is lower than that of the lower part. This is because the PCM preferentially absorbs the heat of the HTF near the inlet of HTF; this is consistent with the conclusion of Zhang, Shengqi et al. [39]. In the PCM part, the PCM begins to melt when the temperature of PCM reaches 325K (the melting temperature of PCM in this study[42]). At the beginning of melting, heat transfer of the PCM is dominated by heat conduction, and a flat thin layer of liquid PCM appears around the fin and inner tube (Fig. 6, 300s).

Moreover, the thickness of the liquid layer is smaller at low temperatures and more significant at high temperatures. After a while, the PCM near the fin and inner tube wall is wholly melted (Fig. 6, 600s), and the density difference of PCM at different temperatures leads to strong natural convection. Therefore, convective heat transfer dominates the melting of PCM at this stage [42]. At the later stage, most of the PCM had melted (Fig. 6, the 1200s), and the influence of natural convection was significantly reduced. During this process, the melting rate of PCM was prolonged. It is worth mentioning that the solid-liquid interface changes during the melting of PCM in this study are like those in many published papers [39, 40, 42, 43]. In addition, the solid-liquid interface is similar for toothed fins with different volumes, but the melting rate is different: the smaller the toothed-fins volume is, the lower the melting rate of PCM is. This indicates that the toothed fins do not change the original PCM's overall melting law but only slightly affect the local area. 90% fin and 100% fin (ordinary fin) are almost the same; this means that toothed fins can achieve the same heat transfer efficiency in a smaller volume.

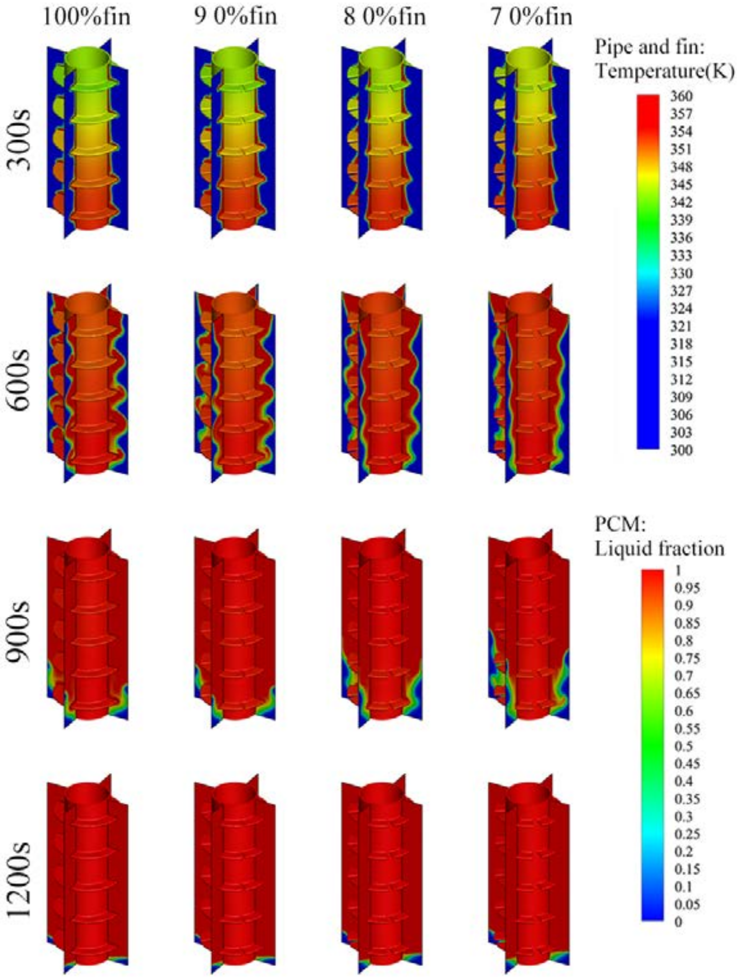


Fig.6. The contours of PCM liquid fraction with different teeth opening volume of fins (The middle part is the inner tube, and the outer part is the two vertical sections of the PCM domain).

Fig. 7 shows the variations of several parameters versus time at different toothed-opening volumes. (a)Liquid fraction, (b)*Nu*, (c) Average natural convection velocity in PCM region, (d)Total melting time. According to Fig. 7(a), The melting time corresponding to 100% - 40% fin is 1610 s - 2020 s, and the total melting time of PCM is increased by 25%. Combined with Fig. 6, these increased melting times mainly come from the later melting stage of PCM (The 300 s, 600 s, and 900 s contours are similar). Nu can reflect the heat transfer intensity between the tube and PCM. It can be seen from Fig. 7(b) that the larger the fin volume is, the greater the heat transfer intensity of PCM;

this is the same as the result of Nie et al. [41]. Interestingly, Nu in the 90% fin's PCM during the first half of the melting process is more significant than that in 100% fin's (ordinary fin) PCM, which indicates that small volume tooth-opening will strengthen the convective heat transfer intensity of PCM during the first half of melting process, this also shows that the use of fins has an adverse effect on the occurrence of natural convection, and this is similar to the conclusion of Kalapala et al. [10].

Fig. 7(c) shows the average velocity magnitude in the melting process of PCM, which can reflect the size of convection. It can be seen from the figure that the velocity of PCM under different fin sizes is very different, and the maximum velocity of 100% fin and 90% fin is close to 0.0007m/s. 80%fin reached 0.0005 m/s, and the rest only 0.0004 m/s. Consistent with the previous conclusions, the average velocity magnitude of liquid PCM decreases with the decrease of fin volume, but toothed-fin with more volume (100% fin - 80% fin) has relatively little effect. The average velocity magnitude of liquid PCM can directly characterize the convective heat transfer intensity of PCM, which means that: the convective heat transfer intensity of PCM decreases with the decrease of fin volume. However, from the perspective of the structure of the annular fin, the existence of the annular fin is not conducive to the generation and development of local natural convection[10]; on the contrary, the toothed fin is conducive to the development of local natural convection. Why is the simulation conclusion of natural convection in this study contrary to the above law? The work of Zhang, Shengqi et al. [39] shows why. They studied the effects of the annular fin and longitudinal fin on the melting process of PCM in a vertically placed heat exchanger. Their conclusion is similar to that in this study, and an annular fin is beneficial to the occurrence of natural convection of PCM in vertically placed shell-and-tube heat exchangers. For this intriguing phenomenon, they suggest that natural convection is enhanced by vortices created between neighbouring annular fins. This is confirmed by the vortices in the streamlines of the liquefied PCM shown in Fig. 8(b).

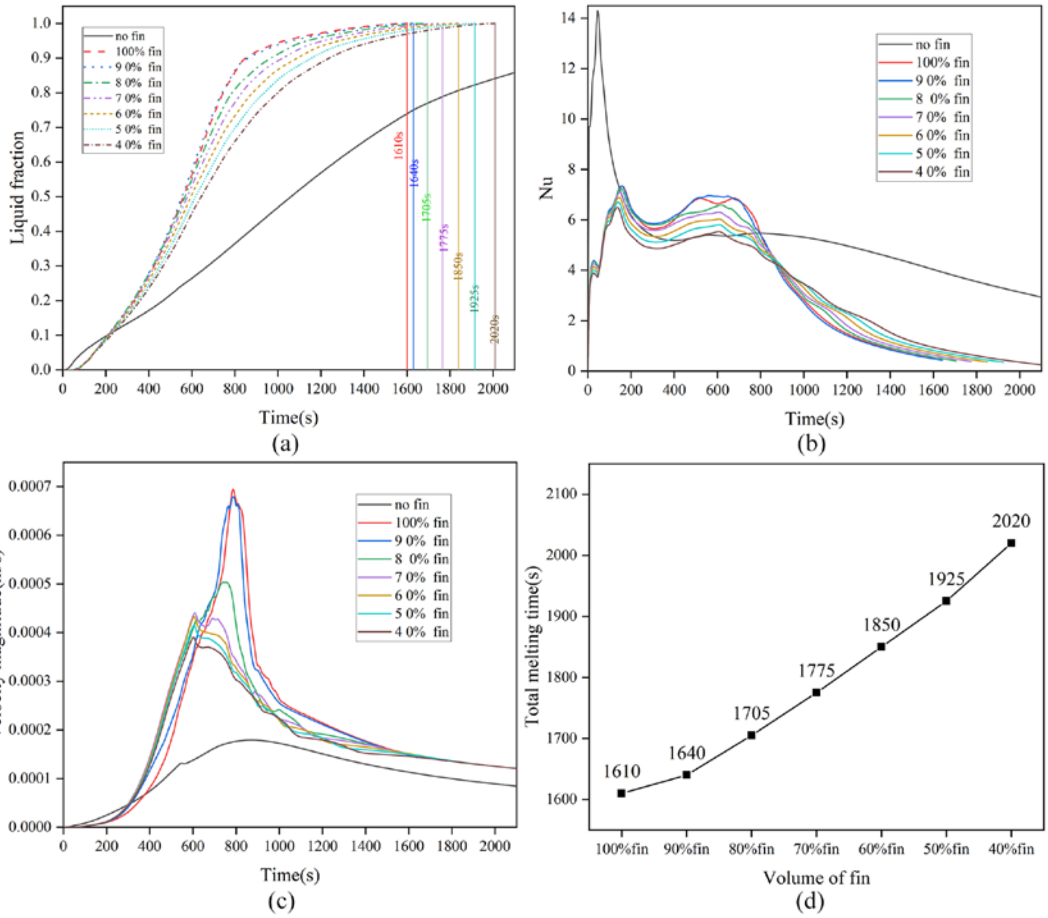


Fig.7. The variations of several parameters versus time at different toothed-opening volumes. (a) Liquid fraction, (b) *Nu*, (c) average velocity magnitude in PCM region, (d) Total melting time.

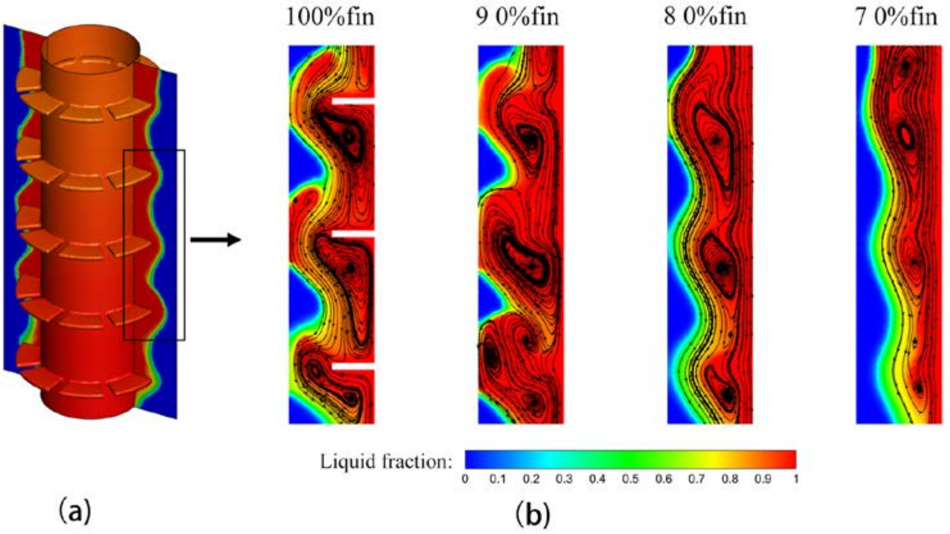


Fig.8. The middle section at 700 s. (a) Section position, (b) Streamlines of the Liquid PCM.

In the previous discussion, the heat transfer performance of PCM of 100%fin and

90% fin are nearly the same over time and the contours of PCM liquid fraction. However, there is a significant difference when the fin volume is less than 80%. Fig. 8 shows streamlines of the liquefied PCM at the middle section at 700s, similar to the conclusions of Shengqi et al. [39] and Zonouzi et al. [40], many vortices appear in the liquid PCM between fins. In addition, the vortices produced by 100% fin and 90% are large and numerous, and the vortices of 90% fin are even slightly more significant than 100%fin, the vortices created by 80% fin are somewhat reduced, and the vortices produced by 70% fin are significantly reduced and smaller. This means that the small volume of toothed-opening will not affect the formation and development of vortices between annular toothed-fins, and even have some promotion effect on it, and the large volume of toothed-opening will have a negative effect on the formation and development of vortex to some extent. Vortex is a kind of strong natural convection, which is conducive to the heat transfer of PCM [40, 50]. The difference between the vortices of 100%fin and 90%fin explains why the heat transfer intensity of 90%fin is greater than 100%fin in the first half of the melting process. In addition, it can be seen from Fig. 9 that in the first half of the melting process of PCM, the larger the fin volume, the more liquid phase PCM in the upper half at "time=600 s". This is because the local natural convection of PCM at the grooves is more intense [51], which is conducive to the upward movement of the high-temperature liquid PCM, while the high-temperature liquid PCM in the upper part cannot affect the melting of the middle and lower part of solid PCM through the natural convection. This is also an essential factor that affects the heat transfer of PCM.

It can be seen from Fig. 7(d) that the total melting time of PCM increases with the toothed-opening volume, and its slope keeps increasing. The melting time corresponding to 100% - 40% fin is 1610 s-2020 s, and the total melting time of PCM is increased by 25%. To accurately describe the enhancement effect of toothed fins and regular fins on the whole melting time of PCM. This study defines a dimensionless coefficient N as:

$$N = \frac{t_{nofin} - t_{ordinary\text{-}fin}}{t_{nofin}} - \frac{t_{nofin} - t_{toothed\text{-}fin}}{t_{nofin}} \tag{11}$$

Where t is the total melting time, this study used t_{nofin} = 3585s, and $t_{ordinary\text{-}fin}$ = 1610s, for annular toothed-fin. Fig.7(d) shows the full melting time of PCM with different volumes of toothed fins. By the definition of N. When the fin volume is 90%, toothed-fin=1610 s, N=0.0084; When the fin is 80%,$t_{toothed\text{-}fin}$=1640s, N=0.0256. This means that when the fin volume is 90% and 80%, compared with the ordinary fin, its enhancement on total melting time decreased by 0.84% and 2.56%, respectively. According to the previous discussion, an annular fin with a volume of 80% - 90% can have less fin volume and little influence on the heat transfer of PCM.

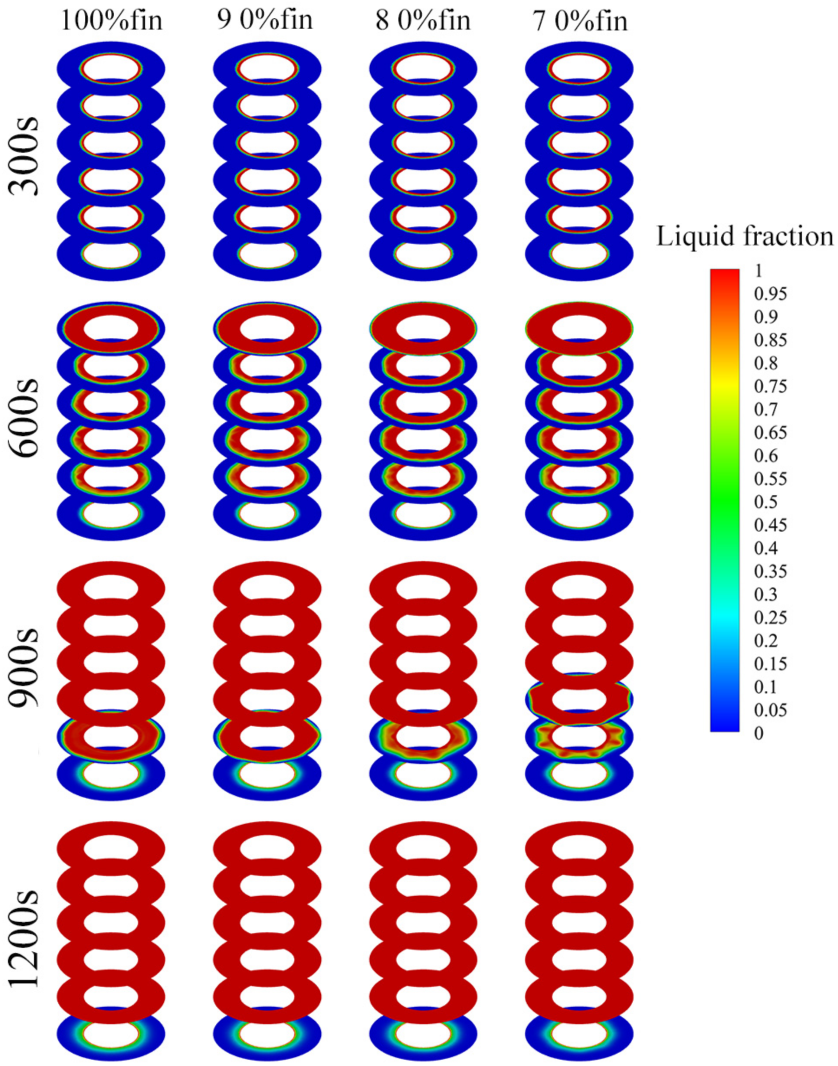
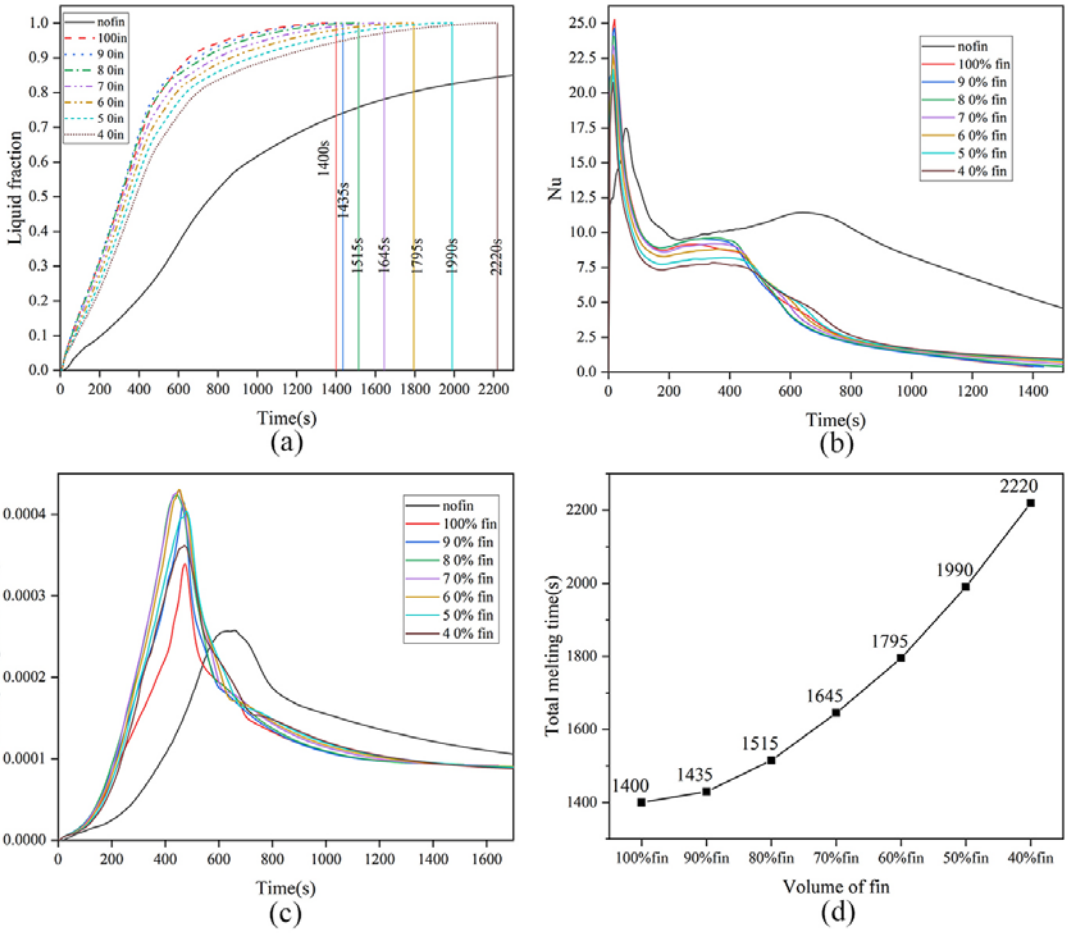


Fig.9. The contours of PCM on several sections with different tooth-opening volume

4.1.2 Longitudinal toothed fin

Fig. 10 shows the variations of (a)Liquid fraction, (b)Nu, and (c) Average natural convection velocity in the PCM region versus with time; and (d)Total melting time. It can be seen from Fig. 10(a) that the melting time corresponding to 100% - 40% fin is 1400 s - 2220 s, and the total melting time of PCM is increased by 44%. Under different volumes of toothed fins, the melting process of PCM is similar, but the melting rate is different; the same conclusion can also be obtained from Fig. 11. The result is like the discussion about annular toothed fin, the liquid phase fractions of 90% fin and 80% fin were higher than those of conventional fins in the first half of the PCM melting process (before 600 s). Fig. 10(c) shows the average velocity magnitude of PCM. Contrary to the conclusion of annular fin, the average PCM flow rate of 90% - 50% fin varies very little, around 0.0004 m/s. The average flow rate of 100%fin is less than 0.00035 m/s, even less than the flow rate of 40%fin. The velocity of all toothed fins is more significant than that of conventional fins, which indicates that toothed fins are conducive to the natural convection of liquid PCM; the toothed fins enhance the natural convection of the PCM. In addition, the melting characteristics of PCM in a horizontally placed LHTE with a longitudinal toothed fin are like that described in the previous section and will not be repeated.



(a) (b) (c) (d)

Fig.10. The variations of several parameters versus time at different toothed-opening volumes. (a)Liquid fraction, (b) *Nu*, (c) average velocity magnitude in PCM region, (d)Total melting time.

Fig. 11 shows the contours of PCM liquid fraction on a grooves section with different volumes of toothed-fin, the contours of PCM liquid fraction of the area obtained in this study are similar to the study of Wu et al. [42]. HTF flows in a horizontal direction, so the temperature of the tube and fin continuously decreases from left to right [39]. Due to the symmetrical structure of this model, only one section (The fourth section) at the grooves is taken in this study to discuss the effect of the toothed fin on the melting characteristics of PCM. It is worth mentioning that the surface area of 100% fin is 2120 mm^2,90% fin is 2210 mm^2, and 80 % fin is 2200 mm^2. Under the same number of teeth, the larger the volume of open teeth, the smaller the surface area of the fin and the smaller the surface area of the fin, the less favourable the heat exchange with the PCM [41]. As shown in Fig. 11, all toothed fins have more volume of liquid PCM in the upper half. In the first half of the melting process of PCM (before 600 s), the liquid phase area of 90%fin and 80%fin is larger than that of 100fin. This indicates that some mechanism exists in the tooth fin to enhance the heat transfer of PCM at the first half of the melting process. According to the previous discussion on the annular fin, the tooth fin is conducive to generating and developing local natural convection; the study by Zhang, Shengqi et al. [39] also illustrates this conclusion from the side.

Therefore, the liquid-phase fraction of 90%fin and 80%fin is higher than that of conventional fin.

In the first half of the melting process, the toothed fin strengthened the local natural convection of PCM. The strengthening of local natural convection is beneficial to the heat transfer of PCM in the early melting stage [40] but also causes the liquid PCM to occupy the upper part of the heat exchanger faster[40, 43]. The top half of the heat exchanger is filled with liquid PCM making the natural convection effect in the upper part lose effect; this is an important reason for the rapid decline of heat transfer performance of toothed fins with a volume below 80. In addition, since the melting of PCM at the bottom of horizontally placed LHTES mainly depends on heat conduction, the smaller the volume of the fin at the bottom, the slower the melting of PCM. This is another crucial reason for the rapidly declining heat transfer performance of toothed fins with a volume below 80.

It can be seen from Fig.10 (d) that the total melting time increases as the fin volume decreases and the slope increases. The melting time corresponding to 100%-40%fin is 1610s-2020s, and the whole melting time of PCM is increased by 25%. In this study, t_{nofin} = 4120 s for longitudinal fin, and the N corresponding to 90%fin is calculated to be 0.0073; N of 80%fin is 0.0279, which means that when the volume of the fin is 90% and 80%, compared with the ordinary fin, its enhancement on total melting time decreased by 0.73% and 2.79% respectively. Therefore, for longitudinal toothed-fin, the volume of toothed-opening is 80%-90% appropriate.

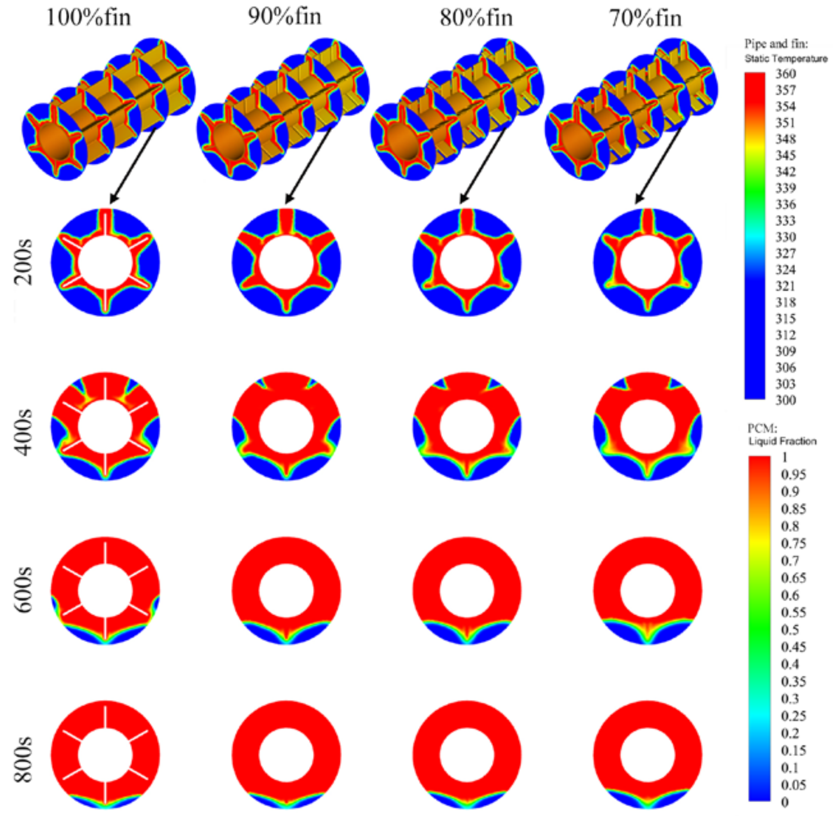


Fig.11. The contours of liquid PCM on a groove section with different toothed-opening volume

4.2 Comparison of different tooth spaces of fins

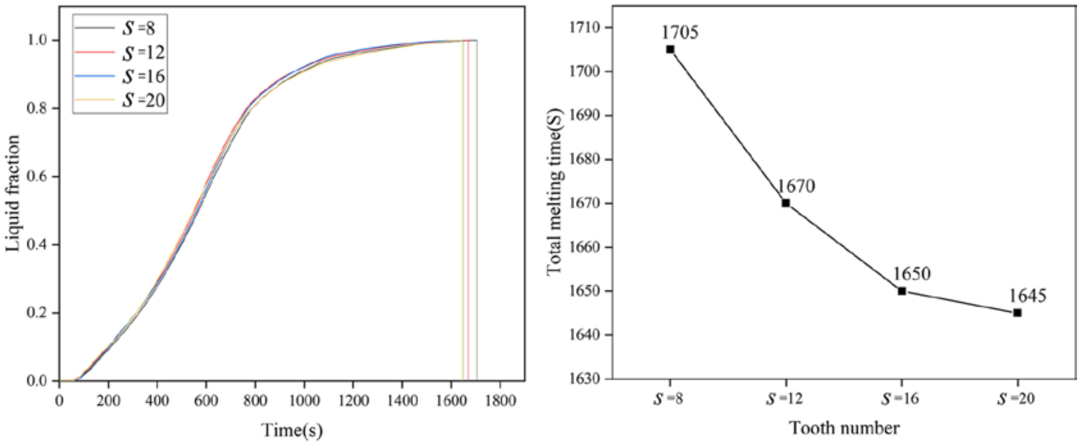
From the discussion in the previous section, the reasonable opening volume is about 80%-90%. To make the toothed-opening effect more obvious, the toothed fins discussed in this section have a volume of 80%. And the melting process of PCM at different tooth spacing (number of teeth) is studied. When the volume is constant, the tooth space is inversely proportional to the number of teeth. "Tooth spacing" and "tooth number" are inversely related, and the physical meaning is the same. In engineering applications, "pitch" is generally used as the fin parameter. Therefore, the longitudinal fin is described as "tooth space". Because of the characteristics of the annular fin structure, there is no "tooth spacing", so only the "number of teeth" can be used to carry out relevant research.

4.2.1 Annular fin

Under the same volume, increasing the number of teeth means expanding the heat transfer area between PCM and fin, which is conducive to heat conduction [41]. At the same toothed-opening volume, the surface area of the toothed fin will increase by 20mm^2 for each additional tooth number, and the increase in fin surface area is beneficial to the heat transfer of PCM [41]. Because PCM has a specific viscosity, when the tooth space decreases (the number of teeth increases), the natural convective heat transfer at the tooth groove is limited due to the viscosity of PCM [52], which protects the development of vortices between annular fin. It can be seen from Fig.12 that the tooth number influences the melting time of PCM, but it is not as important as the tooth volume. When the number of teeth is from 8 to 20, the melting time of PCM is increased by 60s. According to the previous analysis, the reasons for this phenomenon are that the increased surface area of the fin is conducive to the heat transfer of the PCM [41]. However, with the increase in teeth, the enhancement effect of heat transfer is gradually weakened by increasing the number of teeth. The total melting time of PCM with s=16 is only 5 s different from that with s = 20, but the full melting time of PCM with s=8 is 35 s different from that with s = 12. This indicates that an excessive increase in the number of PCM teeth does not affect the heat transfer of PCM. For annular fin there are two reasons for this phenomenon. One is that the increase in heat transfer area mainly affects heat conduction. However, increasing the number of teeth reduces the volume of PCM in a single-tooth groove. When the PCM in a track melts, the temperature of these melted PCM also has symmetry due to the symmetry of the structure (this conclusion about the symmetry of temperature can be observed in Fig.13). The faster the PCM melts between grooves, the faster the temperature along the tooth direction reaches a symmetrical equilibrium, which results in the heat transfer of this part of PCM along the direction of teeth is greatly weakened. The second reasons for this phenomenon is that the limiting effect of PCM viscosity on natural convection is not inversely proportional to the tooth spacing, which is related to the dynamic viscosity coefficient of PCM [53].

In this study t_{nofin} = 3585 s for annular toothed fin. When the number of teeth is 20 N = 0.0098, this means that when the fin volume is 80%, and the number of teeth is 20, compared with the ordinary fin, its enhancement on total melting time decreased by

0.98%.



(a) (b)

Fig.12. (a)Liquid phase fraction varies with time, (b) the total melting time at different numbers of teeth.

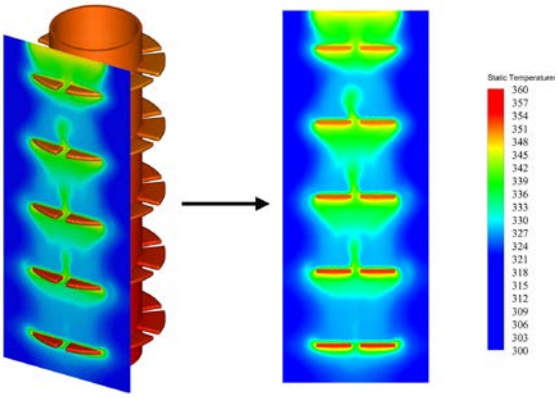


Fig.12. The contours of PCM's temperature on a vertical section.

4.2.2 Longitudinal fin

At the same toothed-opening volume, the effective surface area of the fins corresponding to the tooth space of 2mm is 2200mm, the tooth space of 1.5mm corresponds to the surface area of 2280mm, and the tooth space of 1mm corresponds to the surface area of 2400. And the increase in the fin's surface area benefits the heat transfer of PCM [39]. As seen from Fig. 13, the total melting time of the longitudinal toothed fin also decreases with the decrease of the tooth space, but the slope is decreasing. The total melting time of PCM with d=0.5mm is equal to that of d =1 mm, but the total melting time of PCM with d=2mm is 45s different from that with s =1.5 mm. This proves that further reduction of tooth spacing does not affect the heat transfer of PCM [51]. (Due to the long melting time of PCM, the data monitoring interval in this study was 5 s, so the melting time corresponded to d=0.5mm, Maybe less than 1445 s). There are two explanations for this phenomenon. First, like the annular toothed-fin's description, the rapid realization of the local thermal symmetry balance of PCM limits the effect of fin surface area increase on heat transfer enhancement of PCM. This thermal equilibrium can be seen in Fig. 14. The second explanation of the relationship between the total melting time of PCM and the number of teeth is slightly different from that of the annular toothed fin. However, the principle is the same: because of the viscosity of PCM, the smaller the tooth spacing, the weaker the convective heat transfer in the tooth groove, which is not conducive to the heat transfer of PCM. Considering the heat transfer benefits of the fin manufacturing process, the too-small tooth space is not the better.

In this study, t_{nofin}= 4120 s for annular toothed fin. When the tooth space is 1mm, N =0.0109. which means that when the volume of the fin is 80% and the tooth space is 1mm, compared with the ordinary fin, its enhancement on total melting time decreased by 1.09%

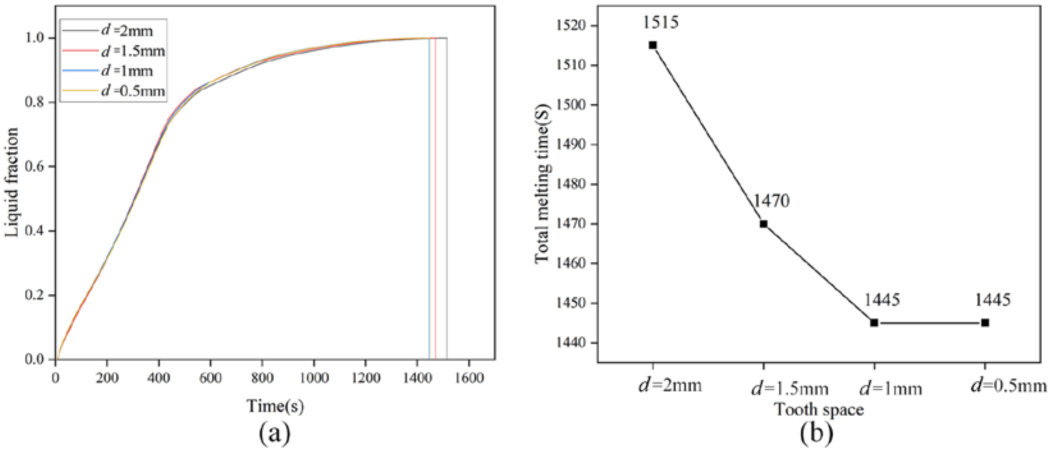


Fig.13. (a)Liquid phase fraction varies with time, and (b) the total melting time at different tooth spaces.

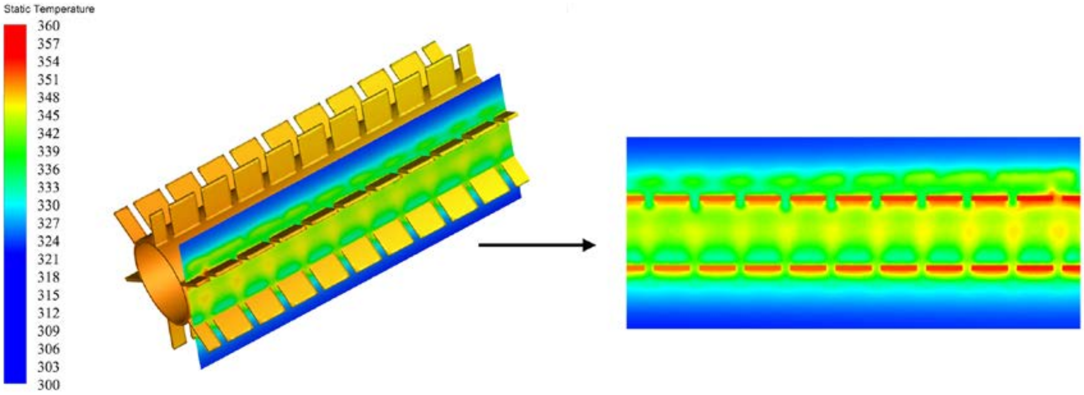


Fig.14. The contour of the temperature of a vertical section. (Left: Section position. Right: Temperature contour)

5. Conclusion

Toothed fins have been used in many fluid heat transfer engineering fields, and studies have shown that toothed fins have higher heat conduction efficiency than conventional fins under the same volume[51, 54, 55]. Fin use can significantly enhance the heat transfer of LHTES, but excessive use of fins will reduce the effective volume of PCM [13] and impedes the natural convection[10]. However, there are few types of research on applying tooth fins in LHTES. To fill the research gap of this subject, this study adopts a numerical simulation method to study the influence of toothed fins on the melting process of PCM. Through the study of the toothed-opening volume and space of the tooth of the toothed fin, the following conclusions are obtained:

(1) Proper toothed opening of fins (appropriate volume and spacing of teeth) can significantly reduce fin volume while slightly affecting PCM's heat transfer performance. Compared with the conventional annular fin and longitudinal fin, the tooth fin volume is reduced by 20%, and the positive effect on the melting time of PCM is reduced by 1.09% and 0.98%, respectively.

(2) Slightly open teeth have little effect on heat transfer performance, but too sizeable open tooth volume leads to a significantly longer melting time of PCM. In two cases in this study, toothed fins with a volume of 70% experienced an increase in melting time of 245s and 165s, respectively, compared to conventional fins.

(3) Under the same opening volume, the reduction of tooth spacing is beneficial to the heat transfer of PCM. In two cases in this study, the tooth spacing was reduced by 2.5 and 2 times, and the melting time of PCM was reduced by 60s and 70s, respectively.

(4) For the annular fin, the recommended toothed-opening volume is 10%-20%, and the number of teeth is 16; the longitudinal fin suggests that the toothed-opening volume should be 10%-20% and the tooth spacing should be 1mm.

(5) The negative influence of toothed fins on heat transfer of PCM mainly root in that the tooth groove area is not conducive to the generation and development of liquid PCM vortices, and the liquid PCM accumulates too quickly in the upper part of LHTES, which is not conducive to natural convection.

Although the effects of the annular fin and longitudinal fin on the melting process of PCM before and after toothed-opening were studied in this paper, many fins with different structures can be toothed-opening. The effect of fins with different structures on the melting process of PCM may be very different. So this is the further research direction of this subject, and the effect of toothed fins on the solidification process of PCM was not discussed in this study. This is one of the research gaps we are considering filling in the next step. In addition, when studying the application of toothed fins in LHTES, the manufacturing cost should also be fully considered.

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