Evaluation on branching fins towards improving latent heat thermal storage

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ABSTRACT

Latent heat storage (LHS) system has obvious advantages in balancing energy supply and demand. However, the heat conductivity of PCM is extraordinarily low, which makes it difficult for the latent heat storage system to be applied in practice. For the sake of enhancing the productivity of phase transformation, the way of adding the area of heat conduction is adopted in this paper, such as adding fins. Two different fin combinations are designed under the condition that the total area of fins is unchanged. They design and analyze from two aspects of fins complexity and angle. The two dimensional model of energy storage equipment was established, and the system containing paraffin RT35 was numerically solved. The melting rate, total time required for melting, melting and temperature changes clouds. According to the analysis of the research results, it is found that the complex fin arranged at the bottom of the phase change material can penetrate deeper into the interior and enhance the melting of the phase change material at the bottom, thereby improving the overall melting rate of the system. When the angle between the fin and the horizontal axis is 0°, the melting rate of the system is faster. From the inner tube to the outer tube, the fins are arranged from short to long. Compared with the simple straight fins, the total melting time is reduced by 52.2%.

Keywords: Latent heat thermal storage; Phase change material; Fins

NONMENCLATURE

Abbreviations	
TES	Thermal energy storage
LHS	Latent heat storage
LHTESS	Latent heat thermal energy storage system
PCMS	Phase change materials
TTHX	Triple tube heat exchange
Symbols	
t	Time （s）
λ	Thermal conductivity (W/m K)
ρ	Density (kg/m^3)
p	Pressure(Pa)
u	Velocity (m/s)
v	Velocity (m/s)
T	Temperature (K)
μ	Dynamic viscosity(N • s/㎡)
h	Total heat (kJ/kg)
β	Liquid component
C_{mush}	Paste region constant
ξ	The minimum value((i.e., ξ = 0.0001)
g	Acceleration of gravity(N/kg)
δ	Coefficient of thermal expansion
c_P	specific heat capacity (J/kg K)
$\triangle$h	Latent heat(kJ/kg)
T_s	Solid phase temperature(K)
T_l	Liquid phase temperature(K)
Γ_{tu}	The walls of the inner tube shell
Γ_{sh}	The walls of the outer tube shell

1. INTRODUCTION

With the increasingly serious problem of energy shortage and environmental pollution in the world, various countries are committed to saving energy and developing new clean and sustainable energy. Solar energy has been vigorously promoted because of its inexhaustible, inexhaustible and clean advantages. Phase change materials [1] in latent heat storage system absorb and release a large amount of latent heat in the process of phase transformation, thus achieving energy storage and release. Therefore, improving the thermal conductivity of phase change materials is the key to improving the efficiency of the whole energy storage system. Ribbed tubes with different structures are one of the most common methods to enhance heat transfer. For latent heat storage system, the fins with high thermal conductivity have the advantages of simple operation and low running cost. The shapes of ordinary fins are mainly vertical, pin, plate and ring. The longitudinal fin is a configuration that takes into account the best performance, especially the cylindrical PCM container.

Many papers researched the influence of creative fins to exchange heat process. Aly et al. [2] compared the property of corrugated fins and flat fins, and proposed the influence of different number and height of corrugated longitudinal fins on the solidification speed of phase change materials. Sheikholeslami [3] verified the effectiveness of snowflake fin structure in the discharge process of large thermoelectric devices. Zhang [4] experimentally studied the use of fractal tree fins to ameliorate energy performance. Hosseinzadeh. [5] proposed snowflake crystal structure containing (Al2O3-GO) HNEPCM on LHTESS. Abdulateef [6] evaluated the horizontal three tube heat exchanger (TTHX). The longitudinal rectangular and triangular fins are numerically studied. The strengthening rates of internal, internal-external, and external triangular fins were 11%, 12% and 15% respectively. There is a significant difference in the strengthening rate of longitudinal fins. Joybari et al. [7] studied the effects of the length, numbers and thickness of fins on the heat transfer phase transition process of triple tubes under the conditions of charge and discharge.

A large number of literatures have proved the benefits of adding fins to the latent heat system. Nevertheless, through the continuous introduction of various innovative fins, the TES system still has a lot of room for improvement. In addition, there is little literature to discuss the effect of fin angle on the phase transition process. Therefore, a new longitudinal stepped fin is proposed to improve the energy storage function of LHTES system, which is a serviceable supplement to the previous research results. The effect of fin angle on thawing rate was also studied

2. MATHEMATICAL MODEL

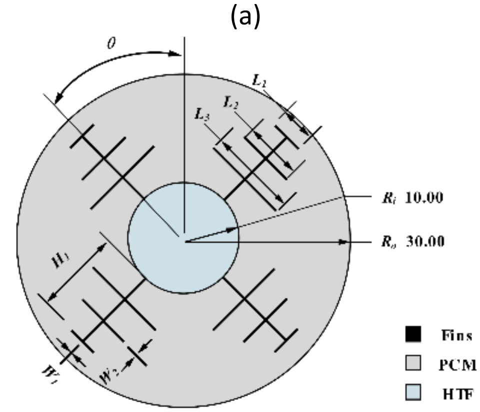
2.1 Description of melting in LHS units

Fig.1 (a) exhibitions the three-dimensional latent heat storage device, which is consisted interior tube, shell, fins and PCM. The heat transfer fluid with higher temperature is distributed in inner tube, and the internal fins are horizontally symmetrical. Fins with ladder shape are arranged on straight fins. The three-dimensional model is simplified to a two-dimensional LHTES device, as shown in **Figure 2** (b). In this model, the thickness of shell and inner cylinder is neglected. The inner tube radius R_i = 10mm, the shell radius R_o = 30mm. The boundary conditions of inner wall and shell are constant temperature and adiabatic respectively. The phase change material in this paper is paraffin wax RT56. Aluminum is finned material. The physical parameters of the material are shown in **Table 1** [8].

2.2 Geometric description

For the sake of improving the melting property of latent heat storage, eight kinds of fin shapes composed of straight fins (d and h) and three fins with raise length make arrangements in long rectangular fin (a-c, e-g). The length of the three fins varies in different order. They range from long to short, the longest in the middle, and from short to long. Consider (a-c) and (e-h) as two sets of fin shapes. The angles of the fins are different.

(a)



(b)

Fig 1. Latent heat energy storage equipment. (a) three-dimensional device; (b) two-dimensional illustration.

Table 1

Thermo-physical properties of materials [8].

Material	Aluminum	Paraffin wax
Phase-change	-	56-57

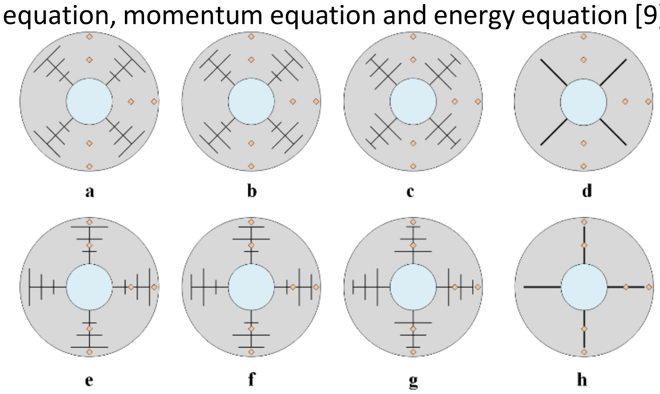
temperature / T_p (°C)		
Latent heat / △h (kJ/kg)	-	232400
Specific heat capacity / c_p (J/kg K)	871	2176
Thermal expansion coefficient / β (K-1)	N/A	0.00075
Thermal conductivity / λ (W/m K)	202.4	0.089(liquid) 0.089(solid)
Viscosity/ ν (kg·m-1·s-1)	N/A	0.00356(liquid) 0.00356(solid)
Density / ρ (kg/m3)	2719	771.2(liquid) 771.2(solid)

2.3 Governing equations

In practical application, the heat dissipation process of LHS unit is complex. For the sake of predict the energy storage and release process, the following simplification is made.

1. Incompressible flow of natural convection laminar flow in phase change materials
2. Viscous dissipation is ignored.
3. The physical properties of phase change materials are constant in liquid and solid phases;
4. PCM includes paste phase, liquid phase and solid phase;
5. The density of PCM follows Boussinesq approximation, and all the other terms are constant except the buoyancy term;
6. There is a local thermal equilibrium between PCM and fin;

In this paper, the traditional enthalpy porosity method is used to resolve the storage process of LHS. The simplified governing equations consist of continuity equation, momentum equation and energy equation [9].



Continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (1)$$

The momentum equations：

$$\frac{\partial(\rho u)}{\partial t}+u\frac{\partial(\rho u)}{\partial x}+v\frac{\partial(\rho u)}{\partial y}=\frac{\partial}{\partial x}(\mu\frac{\partial u}{\partial x})+\frac{\partial}{\partial y}(\mu\frac{\partial u}{\partial y})-\frac{\partial p}{\partial x}+S_u \quad (2)$$

$$\frac{\partial(\rho v)}{\partial t}+u\frac{\partial(\rho v)}{\partial x}+v\frac{\partial(\rho v)}{\partial y}=\frac{\partial}{\partial x}(\mu\frac{\partial v}{\partial x})+\frac{\partial}{\partial y}(\mu\frac{\partial v}{\partial y})-\frac{\partial p}{\partial y}+S_v \quad (3)$$

Energy equation:

For area PCM:

$$\frac{\partial(\rho h)}{\partial t}+\frac{\partial(\rho hu)}{\partial x}+\frac{\partial(\rho hv)}{\partial y}=\frac{\partial}{\partial x}(\lambda\frac{\partial T}{\partial x})+\frac{\partial}{\partial y}(\lambda\frac{\partial T}{\partial y})+S_e \quad (4)$$

For area fin:

$$\frac{\partial(\rho h)}{\partial t}=\frac{\partial}{\partial x}(\lambda\frac{\partial T}{\partial x})+\frac{\partial}{\partial y}(\lambda\frac{\partial T}{\partial y}) \quad (5)$$

In the equation, S_u, S_v, and S_e can be expressed by

$$S_u=\frac{(1-\beta)^2}{\beta^3+\xi}C_{mush}u \quad (6)$$

$$S_v=\frac{(1-\beta)^2}{\beta^3+\xi}C_{mush}v+\frac{\rho_{ref}g\delta(h-h_{ref})}{c_p} \quad (7)$$

$$S_e=\frac{\partial(\rho\Delta h)}{\partial t} \quad (8)$$

The melting process of LHSS unit is put to use enthalpy porosity method [10], in which the tracking and compute of liquid components are carried out by

$$\beta=\begin{cases}0 & (T\le T_s)\\ \frac{T-T_s}{T_l-T_s} & (T_s<T<T_l)\\ 1 & (T\ge T_l)\end{cases} \quad (9)$$

When PCM is completely melted, the porosity is zero, so the speed is reduced to zero. This behavior can be defined by

$$h=h_{ref}+c_p(T-T_{ref})+\beta L_p \quad (10)$$

$$T(x,y,0)=T_0 \quad (11)$$

$$T|_{\Gamma_w}=T_w$$

$$-\lambda\left.\frac{\partial T}{\partial \vec{n}}\right|_{\Gamma_{sh}}=0$$

T_0 is equal to 293.15 K, indicating the initial temperature; Ti is equal to 353.15 K, indicating the wall temperature of the inner tube.

2.4 Numerical method

Two dimensional mesh is divided by unstructured meshes. In this article, fluent-15 commercial CFD software is used for simulation. The finite volume method based on pressure coupled double precision solver is adopted. The governing equation is discretized by second-order upwind scheme, the pressure velocity coupling is solved by simple algorithm, and the pressure correction equation is solved by Presto scheme. The relaxation factors for pressure correction, momentum, energy, physical force and liquid fraction are 0.3, 0.7, 1, 1 and 0.3 respectively. The convergence numbers of the continuity equation, momentum equation and energy equation are 10^{-5}, 10^{-5} and 10^{-6} respectively.

3. RESULTS AND DISCUSSION

In this section, the influence of different fin shapes on the energy storage device can be obtained by analyzing the change of melting fraction, total melting time and cloud diagram of liquid melting fraction of the latent heat energy storage system with eight kinds of fins.

3.1 Analysis of melting process

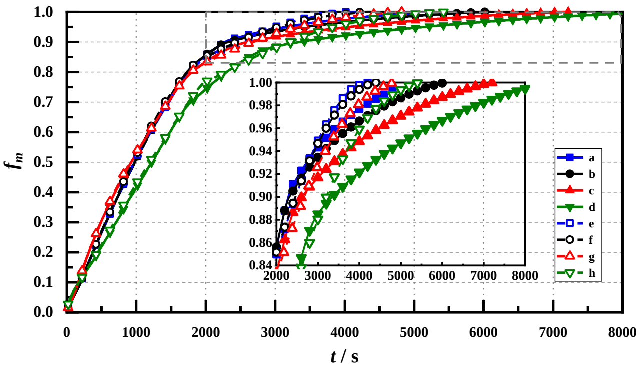


Fig.3. Liquid fraction distraction with the time.

Fig. 3 shows the change trend of liquid fraction of phase change material with time, and the change of fin shape on the heat storage rate of latent heat energy storage system can be obtained. **Fig. 4** depicts the distribution of liquid volume fraction. The thermal conductivity of the phase change material is greater than that of the fin. It can be seen that at 200s, the phase change material first melts around the fin. As the melting proceeds, the paste boundary gradually expands to the periphery. At 2000s, the phase change material above melted completely. It can be found that only a little of the phase change material left has not melted at 3000s. **Fig. 5** shows the total melting time. Compared with **Fig. 3**, it is more intuitive to see the advantage of fin shape in latent heat storage system. The white area represents the time required for the phase change material to melt to 0.75 to fully melt. It can be seen that this part of the time accounts for more than half of the total melting time. As can be seen from the liquid fraction cloud diagram, this part is at the bottom of the device. For fins of the same shape, the time in the red area is basically the same. Therefore, reducing the melting time at the bottom can reduce the overall melting time of the device. The lower part relies on heat conduction for heat transfer, so the longer the fins are arranged near the bottom, the faster the melting of phase change materials.

3.2 Effect of fin bifurcation

Due to the action of gravity, the upper phase change material melts and flows downward, resulting in disturbance and natural convection, which accelerates the melting of the upper phase change material. The lower part mainly depends on heat conduction, so the melting of phase change materials in the lower part needs to be strengthened. From the **Fig.** 3, we can see that except for the two finned shapes of d and h, the variation trend of other fins is nearly the same before 1850s. After that, the liquid fraction gradually changes slowly, and the change of the curve slowly separates. The melting speed of d and h-type fins is the slowest before the 3677s, which shows that the ordinary rectangular fins are not dominant advantage in the early melting stage. The change curve of liquid fraction of d and h-shaped fins intersects, and the d case finally melts. When the liquid melting fraction is in the range of 0.94 ~ 1, the melting rate of e case is the fastest, and then f case. At 2400s, the non-ordinary rectangular fins (a-c, e-f) appeared at a turning point. The liquid fraction at this time is 0.9. By comparing the changes of fins growing out of straight fins, it can be found that longer fins should be arranged near the outer tube, and shorter fins near the inner tube can better improve the melting rate of PCM.

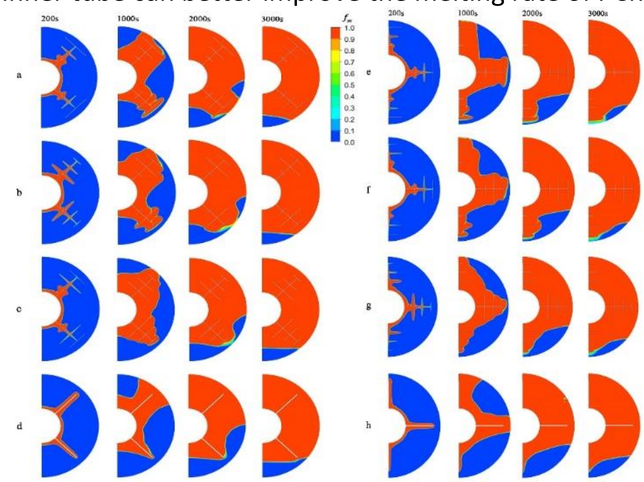


Fig.4. Liquid fraction distraction with the time.

3.3 Effect of fin position.

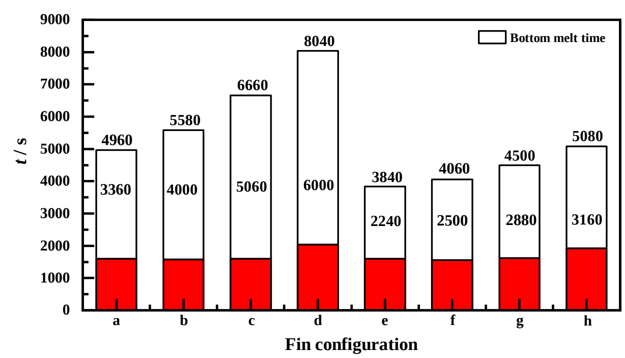


Fig.5. Total melting time and bottom melting time.

Fig. 3 shows that after 4421s, the melting rate of the h case exceeds that of the fin when the angle between the fin and the horizontal axis is 45 °. It shows that to some extent, changing the fin angle can improve the melting speed better than changing the fin shape. When the angle between the fin and the horizontal axis is 0 °, the complete melting time of the phase change material is greater than 45 °. In other words, changing the angle of fins is a very effective way to enhance energy storage efficiency. Compared with d case, the total melting time of (e-h) is reduced by 52.22%, 49.50%, 44.03% and 36.82% respectively.

3. CONCLUSIONS

According to the analysis of eight fin shapes, the following conclusions can be obtained:

(1) Maintaining the total energy storage unchanged, the fins arranged from the inner tube to the outer tube can improve the efficiency of the latent heat energy storage device from short to long.

(2) The adjustment of fin angle has a significant effect on shortening the melting time of the whole phase change material. When θ equals 0 °, the melting efficiency can be improved. The reason is that after the angle changes, the lower fin can go deep into the bottom of the system. The melting time of d case is 2960s longer than that of h case.

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