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Thermal performance of a novel shell-and-tube latent heat thermal energy storage unit with angled fins

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ABSTRACT

Latent heat thermal energy storage is used to solve the problem for the intermittency of time and space for solar energy. To improve the energy storage efficiency, metal fins are typically further added to the shell side to increase thermal conductivity of phase change materials. In this paper, a novel shell-and-tube latent heat thermal energy storage unit with angled fins was designed. A two-dimensional simulation model for an angled-fin tube was established and its melting characteristics were studied, including melting fraction, melting front evolution and complete melting time. Results demonstrated that a 55.41% reduction in full melting time was obtained for the unit with angled-fins. Except too big angles, the melting speed increased. Angled-fin tube can give a perspective to optimization of traditional finned tubes for practical applications with thermal energy storage.

Keywords: Thermal energy storage; Phase change materials; Heat transfer enhancement; Angled fins

1. INTRODUCTION

Global energy consumption is growing rapidly [1]. Solar energy has abundant reserves and is widely distributed around the world. As a sustainable clean energy source, it has received key attentions in practical application [2], including heating, air conditioning, and power generation. However, solar energy is unstable and this problem significantly limit the widespread utilization of solar thermal applications.

Thermal energy storage (TES) devices are used to solve the intermittency of time and the unevenness of space for solar energy [3]. Paraffin is a common industrial TES material with stable thermal properties, non-toxic, non-corrosive, and low price. However, its relatively low thermal conductivity greatly restrain the energy efficiency for TES systems [4]. To this end, a considerable number of studies have been carried out to improve the energy efficiency via increasing thermal conductivity of PCMs. Adding fins is an excellent choice to effectively improve the overall heat transfer for TES system [5].

Liu et al. [7] proposed that metal fins in heat storage materials can significantly improve its thermal conductivity. Zhang et al. [8] confirmed the enhancement effect of fins on phase change heat transfer, as well. Yang et al. [9] conducted a numerical simulation study on the melting process of paraffin with annular fins, and found that by inserting the annular fin in PCM, the complete melting time can be maximally saved by 65%.

The strengthening effect of the fin is affected by the flow conditions, position and structure of the fin. Kang et al. [10] conducted experiments on the heat transfer and resistance characteristics of 9 types of straight finned tubes. They found that the effect of fin spacing on heat transfer depends on the critical Reynolds number. Erek et al. [11] studied the energy storage system with radial finned tube structure through numerical simulation and experiment. The results showed that the solidification of the PCM around the fin tube was affected by Reynolds number, fin diameter and fin spacing. For cylindrical PCM containers, rectangular longitudinal fins have the best effect, followed by circular, plate, and pin ones [12]. Furthermore, there are many novel shapes of longitudinal fin. Triangular structure [13], tree-shaped structure [14], V-shaped fin [15], snowflake-shaped fin [16] and topology structure [17] have been proposed. Compared with traditional fins, the innovative fin structure can save more than 10% of the melting time.

To be conclusive, fins are typically inserted into the PCM domain to enhance their effective thermal conductivity; and the overall phase change process can be effectively accelerated due mainly to more PCM

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domain influenced by fins with high thermal conductivity. Therefore, angled-fins with simple processing technology and traditional rectangular structure are selected in this paper. In order to provide a better LHTES unit with fins, two-dimensional simulation models for a finned tube with angled-fins were established. Comparative studies on straight fin and angled-fin with different angles and different directions were performed. The characteristics of the melting process are further studied, including melting fraction, propagation of melting front, melting time. Angled-finned tube is able to give a perspective to optimization of traditional finned tubes for practical applications with thermal energy storage.

2. NUMERICAL SIMULATION

2.1 Physical model and computational domain

Fig.1 described schematically the physical model for the TES unit with angled-fins. The TES cylinder has a height of 270mm and a diameter of 90mm. The inner pipe was made of copper with an inner and outer diameter of 20 mm and 22 mm, in respective. Heat transfer fluid (HTF) flows through the inner copper tube with a temperature of 70 Celsius degree and a velocity of 1.0 m/s. Annular fins with a thickness of *t*, a height of *h*, an angle of *ϑ* are equally distributed on the outer surface of the copper tube. Paraffin that served as PCM was filled in the annulus.

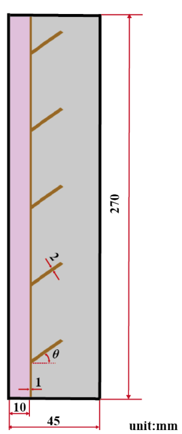

Fig. 1. Design of the TES unit with angled-fins.

2.2 Governing equations

The transient heat transfer was described as follows:

$$\nabla \cdot \vec{u} = 0 \tag{1}$$

$$\rho_f \frac{\partial \vec{u}}{\partial t} + \rho_f (\vec{u} \cdot \nabla)\vec{u} = -\nabla P + \mu_f \nabla^2 \vec{u} + \rho_f \vec{g} \beta (T_f - T_m) + A\vec{u} \tag{2}$$

$$\rho_f c_{pf} \frac{\partial T_f}{\partial t} + \rho_f c_{pf} \vec{u} \cdot \nabla T_f = \nabla \cdot (k_f \nabla T_f) - \rho_f L_f \frac{\partial f_l}{\partial t} \tag{3}$$

where the coefficient *A* in Eq.(2) donated the damping coefficient to damp the velocity in solidified phase, which can be calculated through the following equation [18]:

$$A = \frac{C(1-f_l)^2}{S + f_l^3} \tag{4}$$

where *C* and *S* were the numerical coefficients, recommended to be very large (1×10^{15}) and small (1×10^{-10}); f_l was the melting fraction of PCM and it was determined by the representative temperature in the mushy zone:

$$f_l = \begin{cases} 0 & \text{at} \quad T < T_{\text{solidus}} & \text{solid} \\ \dfrac{T - T_{\text{solidus}}}{T_{\text{liquidus}} - T_{\text{solidus}}} & \text{at} \quad T_{\text{solidus}} < T < T_{\text{liquidus}} & \text{mushy} \\ 1 & \text{at} \quad T > T_{\text{liquidus}} & \text{liquid} \end{cases} \tag{5}$$

3. RESULTS AND DISCUSSIONS

3.1 Comparisons of melting fraction

Fig.2 shows the effect of angled fins on melting fraction. The melting fraction with the angled fins begins to diverge after 1000s. There is a significant difference in the melting fraction during 3000 s-5000 s. As shown in the enlarged view on the left side of Fig.2, the melting rate reaches maximally and minimally 0.7 and 0.3, in respective. As for smaller angles, there is not much difference between them with respect to melting fraction.

In the later stage of the melting process, the melting time varies significantly with the direction and angle of fins. As shown in the enlarged view on the right side of Fig.2, when the angle range is 5°-15°, the down angled-fins complete melting before the upper angled-fins do. For a range of 30°-75°, the completion of melting for upper angled-fins is earlier than that for the down angled-fins. When maintaining the same direction, the melting rate of the upper angled-fins decreases with the increase in the angle, and the trend of the down angled-fins is similar.

Importantly, it can be found from Fig.2 that compared to a finned tube with straight fins (angle of 0), angled-fins can greatly increase the melting fraction at the same time, and the melting rate is also greatly improved. However, the melting process of angled-finned tube with too large angles is deteriorated.

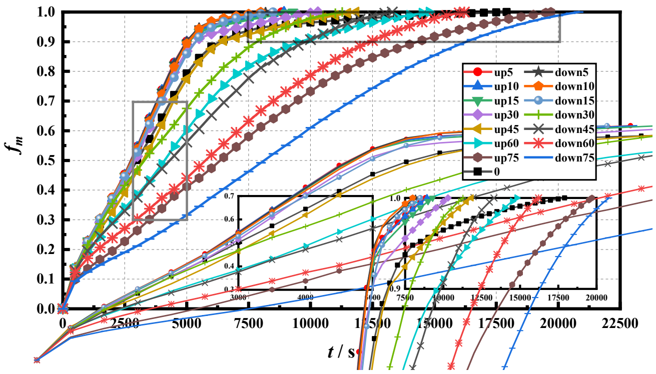

Fig. 2. Effect of angled fins on melting fraction.

3.2 Propagation of melting front

Fig.3 shows the melting front morphology of the angled-fin and the straight-fin tube at 2000 s, 4000 s and 6000 s. Generally, regardless of fin angles, the heat conduction efficiency along the fins is higher, leading to the fact that PCMs close to the fins have a higher melting fraction; while PCMs far away from fins have a smaller one. The fins have a promotion effect on the melting of PCM around fins. The affected area by each fin is in the shape of a funnel. The melting front morphology of the entire heat storage tube is wavy, that is, a continuous funnel. The morphology of the phase interface is significantly affected by the fin. As shown in Fig. 2(a), when the fin swings upward, the fin with high thermal conductivity is beneficial to the melting of the area above the fin. The difference in small angle range (5°, 10°, 15°) is not obvious. When angle is greater than 30°, the melting area of each fin expands upward, the radial melting decreases, the funnel shape becomes thinner and longer, and the wave crest of the phase interface is smaller. When the angle reaches 75°, the melting area affected by the fins is almost attached to the inner copper tube, and the melting fraction of the radial PCM is very poor. When the fin swings downward, the radial phase interface morphology is like that of the upward swing, and the melting area of each fin becomes narrow and expands downward.

At 4000 s, the melting fraction further increases, the melting area of the finned tube with straight fins is still a continuous funnel, and the phase interface morphology is wavy. All of the PCM in the upper area of the top fin has been melted. The funnel-shaped melting area around each fin gradually becomes smaller from top to bottom, and the melting of the heat storage tube is uneven in the vertical direction. The upward and downward swings (5°, 10°, 15°) in a small angle range make the melting area larger, and the unevenness in the vertical direction is smaller than that of the straight fin. The large-angle swing slows down the melting front in the radial direction, making the melting fraction of heat storage tube worse than that of the straight fin tube.

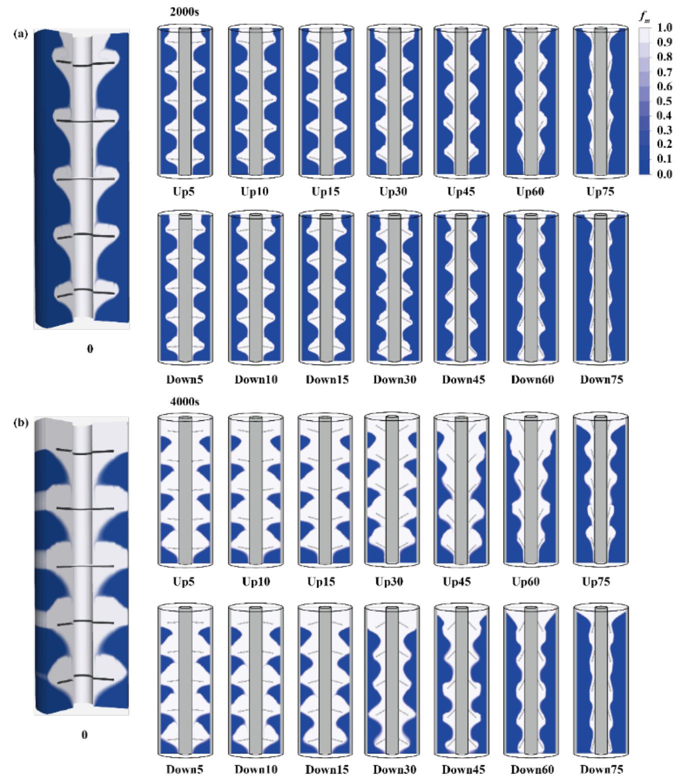

Fig. 3. Melting front distributions of angled-fins at t = (a) 2000s and (b) 4000s.

4. CONCLUSIONS

This paper proposes a novel finned tube with angled-fins for enhancing solid-liquid phase change heat transfer. Comparative studies on straight and angled fins with different angles and different directions are performed. The characteristics of the melting process are further studied, including melting fraction, propagation of melting front, and the complete melting time. The significant conclusions drawn from the results are summarized below:

1) Swinging the fin up or down can expand melting area near fin and promote the vertical melting, while the radial melting is weakened. However, an excessively large angle leads to deteriorations of the entire melting process.

2) Compared to finned tube with straight fins, a 55.41% reduction in complete melting time in the PCM region is obtained for the TES unit with angled-fins.

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