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Melting performance analysis of phase change material in latent heat storage unit with Y-shaped fins

Zhan Liu[1], Zihui Liu[1], Xuqing Yang[1], Xiaohu Yang[2,*]

1 College of Electromechanical Engineering, Qingdao University of Science and Technology, Qingdao 266061, PR China

2 School of Human Settlements and Civil Engineering, Xi’an Jiaotong University, Xi’an 710049, PR China
(Corresponding Author: xiaohuyang@xjtu.edu.cn)

ABSTRACT

Latent heat storage (LHS) can improve the imbalance of energy supply and demand. However, the relatively low thermal conductivity of phase change materials (PCMs) may weaken the advantage of latent heat storage. In this paper, seven different fin combinations are designed for LHS device filling with paraffin wax RT56 as PCM. The fins are composed of straight and Y-shaped ones. For the same volume ratio of fins to PCMs, the width and height of fin are changed to study their effect on melting phase change. A 2D model is established and is solved numerically. Comparing of phase interface evolution verifies the established numerical model. Results show that the melting speed of PCM at the bottom of LHS device is slow, and the Y-shaped fin with longer part in the lower region for PCM can help heat penetrate into the interior of PCM, and promote the heat conduction inside the lower PCM, thus improving the overall melting performance. The PCM melting time of the unit with increasing fin height is shorter than that of the device with increasing fin width.

Keywords: Latent heat storage; Phase change material; Y-shaped fin; Straight fin; Shell-and-tube heat exchanger

1. INTRODUCTION

Thermal energy storage (TES) plays a potentially important role in the utilization of renewable and fossil fuel energy. TES is widely used in many industrial fields, including heat recovery [1], electric energy cooling [2] and sustainable energy exploitation [3], which helps to alleviate the mismatch problem of energy supply and demand.

Latent heat storage (LHS) method uses phase change materials (PCMs) to absorb or release heat during solid-liquid phase change. Phase change energy storage system has the advantages of large energy storage and almost constant working temperature [4]. LHS is considered to be a better energy storage pattern than thermochemical and sensible heat energy storage system. Esen et al. [5] studied the thermal storage performance of different PCMs. They found that PCMs not only had high energy density, but also had small size, flexible design convenient use and easy management. Research results showed that the thermal performance of LHS unit mainly depended on the thermo-physical properties of PCMs as well as the structure of LHS unit. However, the relatively low thermal conductivity of PCMs may limit the high energy charging/discharging efficiency of the TES system. Regarding this issue, there are many ways to improve the productiveness of latent heat storage, including adding fins, porous matrix, hybrid nanoparticles and multiple PCMs.

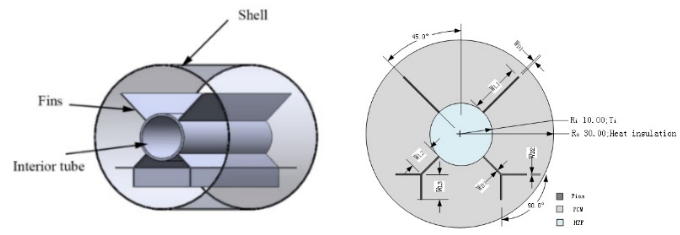
A large body of studies attempted to explore the influence of creative fins on the thermal performance during phase change. Aly et al. [6] studied the effects of corrugated longitudinal fins with different numbers and heights on the solidification of PCMs. The performance of corrugated fin and flat fin was compared. Joybari et al. [7] investigated the influence of fin length, number and thickness on the triplex tube phase change process under the simultaneous charging and discharging conditions. The effectiveness of a snowflake fin structure in the discharge process of a large pyroelectric device was verified by Sheikholeslami [8]. Zhang [9] experimentally used the fractal-tree-shaped fins to improve energy performance. A horizontal triple tube heat exchange (TTHX) was evaluated by Abdulateef [10]. Two kinds of extended surfaces, longitudinal and triangular fins, were numerically studied. Among them, the strengthening rates of inner, inner and outer triangular fins were 11%, 12% and 15%, respectively. To further enhance melting heat transfer, nanoparticles and fins were both employed as thermal spreaders inside PCMs. Mahdi [11] studied the effects of using fins alone, using nanoparticles alone and their combination on solidification process. It was found that the combination outperformed each single structure.

When the fin volume occupies the majority, the volume of PCM decreases, resulting in a decrease in the energy storage capacity. On the contrary, if the volume of fin is too small, it cannot penetrate into the interior of PCM, so that the method of increasing the melting rate by adding fins will be limited. Therefore, to find a solution that fins occupy a small volume but simultaneously has a strong thermal penetration is desired. In this paper, it is proposed to distribute the straight and Y-shaped fins in LHS device with different combinations, keeping the cross-sectional area of fins accounting for 1.3% as the volume ratio of fins to PCMs. By adjusting the length, width and shape of fins, the melting heat transfer and energy storage efficiency can be further improved.

2. MATHEMATICAL MODEL

2.1 Physical model of the LHS units

Fig.1 (a) shows the three-dimensional LHS device, which is composed of interior tube, fin, shell and PCM. The fin distribution of the LHS device is straight fin in the upper part and Y-shaped fin in the lower part. According to the simulation and analysis results below, the fin with this shape has the most advantage in improving the solid melting rate. On the basis of the previous research, the axial temperature gradient of LHS is far less than the horizontal direction. Therefore, the three-dimensional model can be replaced by the melting heat transfer in the two-dimensional LHS one shown in Fig. 1 (b). The heat transfer fluid (HTF) flows through the inner tube and PCM fills the gap between the inner tube and the shell. In this model, the thickness of shell and inner cylinder is ignored. The shell radius R_o = 30mm, the inner tube radius R_i = 10mm. In practical application, in order to prevent energy loss, LHS device is wrapped with insulation material, and the temperature of heat transfer fluid flowing through the inner tube is assumed to be constant. Therefore, the boundary conditions of shell and inner wall are adiabatic and constant temperature respectively. In this paper, paraffin RT56 was used as PCM. Aluminum is used as fin material because of its light weight and high thermal conductivity. The physical parameters of materials are shown in Table 1 [13].



(a) (b)

Fig. 1. Latent heat storage device.

Table 1
Thermo-physical properties of materials [13].

Material	Aluminum	Paraffin wax
Phase-change temperature / T_p (°C)	-	56-57
Latent heat / $\triangle h$ (kJ/kg)	-	232400
Specific heat capacity / c_p (J/kg K)	871	2176
Thermal conductivity / λ (W/m K)	202.4	0.089 (liquid) 0.089 (solid)
Density / ρ (kg/m3)	2719	771.2 (liquid) 771.2 (solid)

In order to compare the heat transfer enhancement effect, seven kinds of fin structures composed of straight fins and Y-shaped fins are designed, as shown in Fig.2. The straight fin serves as the comparison basis (see Fig. 2(a)) determines the volume ratio of fin to PCM. Fig. 2(b) - (d) is a group with the same length as basic fins, both of which are 16mm. Fig. 2(e) - (g) is another group with the same width as basic, both of which are 0.5mm. The specific geometric dimensions showed at Table 2.

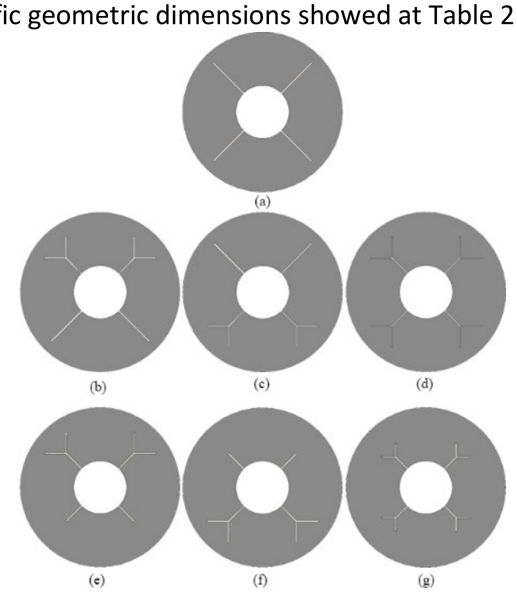


Fig. 2. Schematic diagram of different types of fins.

Table 2

The geometric dimensions of fins.

Cases	WD1/ mm	WD2/ mm	WD3/ mm	WL1/ mm	WL2/ mm	WL3/ mm
basic	0.5	-	-	16	-	-
up-height	0.4	0.4	0.4	16	8	8
down-height	0.4	0.4	0.4	16	8	8
double-height	0.3	0.3	0.4	-	8	8
up-width	0.5	0.5	0.5	8	8	8
down-width	0.5	0.5	0.5	8	8	8
double-width	0.5	0.5	0.5	-	8	4

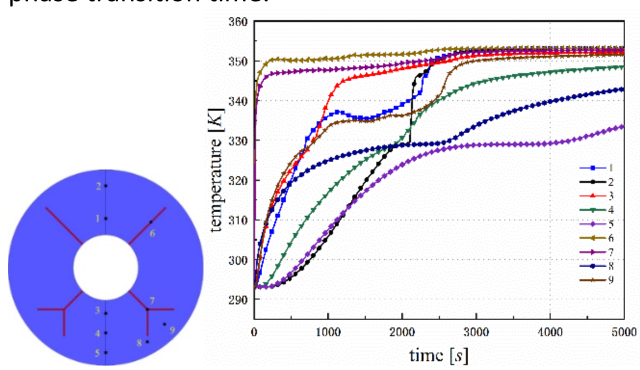
2.2 Numerical method

In this paper, the traditional enthalpy porosity method is used to solve the storage process of LHS. The simplified governing equations include continuity equation, momentum equation and energy equation [14]. The unstructured grid is used and ANSYS-fluent 18.2 is used for numerical simulation. The finite volume method is used based on the pressure coupled double precision solver. The governing equations are discretized by the second-order upwind scheme. The pressure velocity coupling is solved by simple algorithm, and the pressure correction equation is solved by Presto! scheme. For better convergence, the relaxation factors of momentum, pressure correction, energy, physical force and liquid fraction are 0.7, 0.3, 1, 1 and 0.3, respectively. The convergence of the continuity equation, momentum equation and energy equation are 10^{-5}, 10^{-5} and 10^{-6}.

3. RESULTS AND DISCUSSION

3.1 Analysis of melting process

Because the thermal conductivity of fins is 2274 times that of PCM, the heat transfer around fins is faster. Initially, PCM melts around the fins and then diffuses outward gradually, as shown in Fig. 6. At 800 s, the liquid around the upper fin is significantly more than that of the lower part, and only the solid at the bottom does not melt at 3000 s, indicating that the melting speed of the upper PCM is faster than that of the bottom. On the one hand, it can be seen from Fig. 4 that at 5000S, the temperature at points 5 and 8 are 4K lower than those at (points 1-2), meaning that the melting rate at the bottom is very slow. It takes at least 1015 s for other points to reach 340 K, but the temperature of (points 6-7) is measured on the fin which reaches within 40 s, indicating the necessity of adding fins in PCM. On the other hand, the gray shaded portion of Fig. 5 displays the time required for complete melting when the bottom remains the same volume. The melting time required for the bottom up width is 50.4% of the total melting time, which is the smallest among the seven fin combinations. The results exhibit that the bottom melting time increases the total melting time of LHS. The reason for the above phenomenon is that in the process of the upper PCM melt flowing down the tube wall, part of the liquid flows along the inner wall of the tube, causing disturbance to the upper part, and natural convection occurs in the upper part, which strengthens the heat transfer. However, the lower part mainly relies on heat conduction, which leads to slow heat transfer and long phase transition time.



(a) (b)

Fig.4. Temperature curve of points in down height.

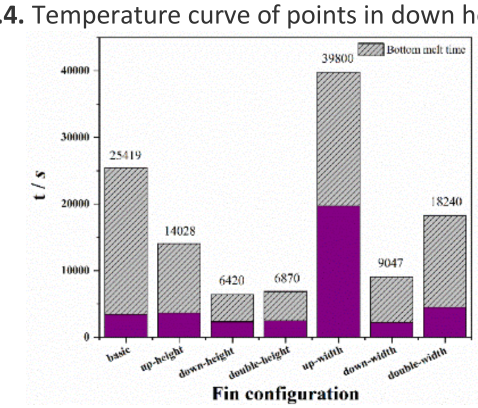


Fig.5. Total melting time and bottom melting time.

3.2 Effect of fin bifurcation.

The melting time of basic and up width is 25419 s and 39800 s respectively according to Fig. 5. What they have in common is that the lower part is straight fin. The length of straight fin in the lower part of up width is 8 mm shorter than that of basic, so it cannot penetrate into the interior of PCM. Although the lower part of up height is also straight fin, the melting time is 11391 s shorter than that of basic. The reason is that the melting rate of the relatively long Y-shaped fin distributed in the upper part is accelerated, leading to the whole melting. The melting time of down height is the shortest, which is 6420 s. The lower Y-shaped fin also shortens the melting time of width height. It can be seen from Fig. 3 that the time required for double height fins to reach a certain liquid fraction is the shortest and the melting rate is the fastest. Compared with other fins, the melting time of double height is 6870 s, which is similar to the melting time of down height and down width. According to the above analysis, the fin bifurcation can significantly enhance the heat transfer rate.

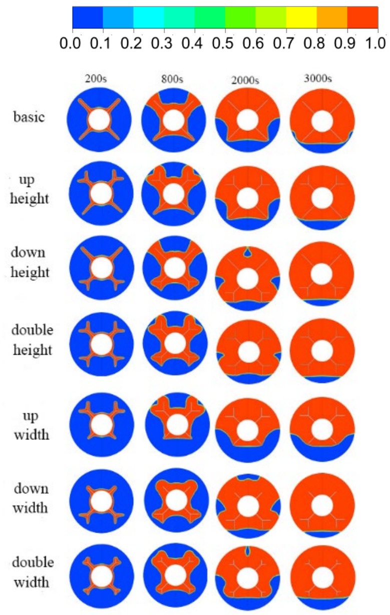


Fig.6. Liquid fraction distraction with the time.

It can be seen from Fig. 5 that the melting time of equal height fins is less than that of equal width fins, and when melting to 1200 s from Fig. 6, the image manifests that the melting liquid area of equal height fins is larger than that of equal width fins. Depicted in Fig. 3, when the up height and up width melt to 80%, up width uses 3598s more than height width, and under the same shape, the equal height of fins is greater than that of equal width fins. It is concluded that the increase of fin length can accelerate the melting of PCM than the increase of fin width.

3. CONCLUSIONS

The advantages of Y-shaped fin compared with straight fin and the effect of fin length and width on melting rate were studied. By comparing the post-treatment of seven fin combinations, the Y-shaped fin in the lower part can enhance the energy storage efficiency more than the straight fin. Fin height has a greater effect on PCM melting rate than its width.

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