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A study on the effect of metal foam tube's bottom cross-cut on heat transfer performance

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Abstract— Metal foam has excellent characteristics to improve the performance of heat transfer in the latent thermal energy storage. However, as for horizontal heat storage tube, the refractory problem at the bottom leads to reduce heat storage efficiency. In this Manuscript, we cut off the bottom of horizontal tubes with different ratios to explore the influence on heat storage efficiency. Through the method of experiment and numerical simulation comparison, the melting fraction, melting interface and velocity field are obtained. The results showed that the smaller the bottom cross-cut ratio, the faster the melting rate. When the bottom cross-cut ratio is 0.6, the complete melting time is the least, 1120 s, which is 18.841 % shorter than that of the round tube.

Keywords—metal foam, heat transfer, bottom, numerical simulation

NONMENCLATURE

Abbreviations

LTES	Latent thermal energy storage
PCMs	Phase change materials
HTF	Heat transfer fluid

Symbols

f_m	Melting fraction

I. INTRODUCTION

Among new energy sources, solar energy is considered to be an important development object that can alleviate energy and environmental problems.

Besides, the latent thermal energy storage (LTES) can greatly reduce energy consumption. In order to solve the problem of low thermal conductivity of Phase change materials (PCMs), the metal foam has excellent characteristics such as high porosity, low density, and large specific surface area to makes it widely used in thermal conductivity and electrical conductivity [1].

Zhang et al [2] studied the thermal conductivity of copper foam on improving paraffin wax through experiments and numerical simulations. The results showed that there is a thermal imbalance effect between the foamed copper ligament and the paraffin, resulting in a large temperature difference. Caliano et al [3]conducted a numerical simulation of the charging and discharging process of pure PCM unit and PCM unit filled with aluminum metal foam through comparison, and the results elaborated that the charging and discharging processes with metal foam were four times and two times faster than those without metal foam, respectively. Metal foam mainly affects the phase transition process by changing the strength of thermal conductivity and natural convection[4]. The small pores and large surface area of metal foams can generate strong guest interactions, which are beneficial to reduce leakage problems of liquid-phase PCMs [5]. Yao et al [6] analyzed the effect of porosity in the range of 0.929~0.974 and the pore size of 5~40 PPI copper foam on the heat transfer of the phase transition process. The heat transfer model can be known by the Rayleigh number.

To improve the adverse effect of the refractory problem at the bottom of the heat storage tube on the overall heat transfer efficiency, this paper explores the issue from another point of view: in the simplified two-dimensional phase change heat storage structure, the bottom heat storage tube is cut off according to a certain proportion, thereby reducing the refractory solid-phase PCM at the bottom of the heat storage tube. Exploring heat transfer modes that can improve heat transfer efficiency and reduce the time to complete melting by changing the bottom cross-cut ratio.

II. NUMERICAL MODEL

A. Model development

Taking one tube of the shell-and-tube TES tank to study, heat transfer fluid (HTF) flows into the system. Besides, the water temperature is 70 ℃ and the initial temperature of PCM is 20 ℃. To simplify the issue, we choose one of the concentric tubes to be the research object. The diameter of the inner heating tube *r* is 20mm, the outer diameter of the heat storage tube R_1 is 60 mm. Porosities of 98 % and pore density of 10 PPI is used for copper porous medium between inner and outer tubes. Regarding the premise that the annular heat storage volume remains unchanged, the bottom of the heat storage tube is cross-cut, and the shape of it is shown in Fig. 1 (a). The bottom cross-cut ratio of different cases is shown in Table 1. Because of the axial-symmetry nature of the shell-and-tube TES unit, an axial-symmetric two-dimensional computational domain was built in Fig. 1 (b).

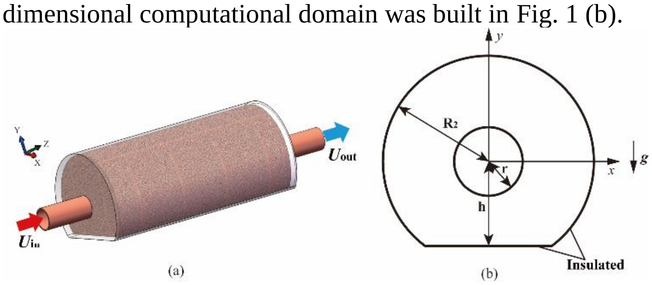


Fig. 1 (a) its annulus bottom-cross-cut LHTES unit; (b) bottom-cross-cut for computational domain

TABLE I The bottom cross-cut ratio of different cases

Case	*Ratio=h / R_2*	*h*/mm	*R_2*/mm
Case A	0.5	16.72	33.45
Case B	0.6	19.44	32.39
Case C	0.7	22.06	31.52
Case D	0.8	24.65	30.81
Case E	0.9	27.26	30.28
Case F	1.0	30	30

B. Model validation

In order to verify the accuracy of the established numerical model, the temperature at two points of case (F) in the numerical model and the experimental model were selected for numerical comparison. Point a and b was located at *R*=25, 11mm, respectively. From the comparison results in the Fig.2, the maximum error between the measurement point a of the simulation results and the experimental measurement point is 3.98 %, which is within the acceptable range.

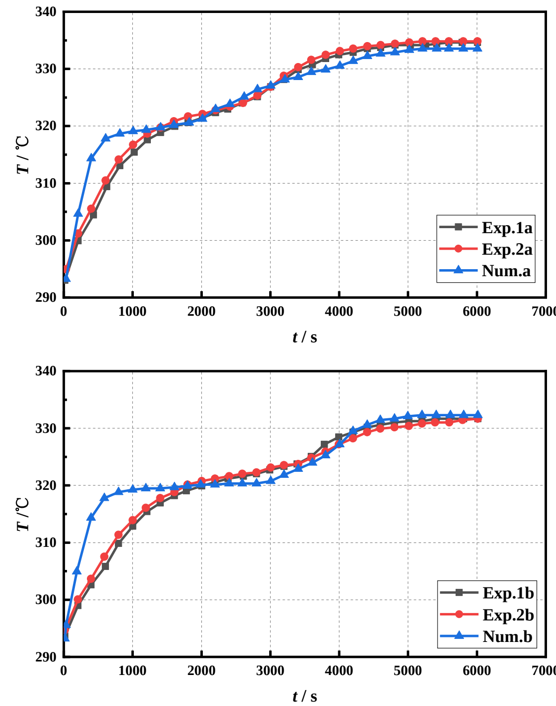


Fig. 2 Comparison of temperature curves of experimental and numerical results at point a and b

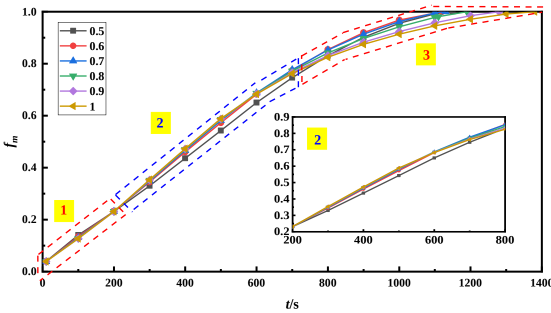
III. RESULTS AND DISCUSSION

A. Melting fraction

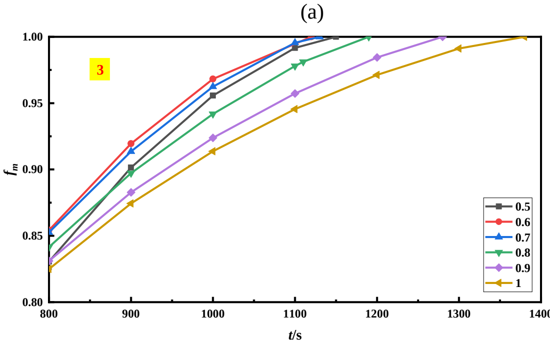
Fig. 3 (a) shows the melting curves of the metal foam-PCM heat storage tube with different bottom cross-cut ratios. Different excision ratios have a significant effect on the development of the melting process. In the early stage of melting, the main heat transfer method is heat conduction. As melting process going on, a corresponding temperature gradient is generated inside the PCM, which in turn generates natural convection to affect the development of the melting process. Due to the change of the cross-cut shape of the heat storage tube, the effect of natural convection in different regions of the tube is different, so that the melting curves of different heat storage tubes have discrepancy. Finally, there is the third stage of the end of melting, which is shown in Fig. 3(b). The melting area develops to the bottom of the heat storage tube. Since the bottom is solid-phase PCM, the main heat transfer mode is changed to heat conduction. The closer the distance to the heating tube, the faster the heat conduction rate, the smaller the solid volume at the bottom of the heat storage tube, and the faster the melting rate.

Taking the melting fraction of the bottom cross-cut ratio of 1 as a reference, at 200 s, the melting rate under different ratios does not differ by more than 0.866 %. At 500 s, the melting fraction of ratio 1 is 0.589, the melting fraction of ratio 0.6 is 0.573, and the melting fraction of ratio 0.5 is 0.543, which are 2.716 % and 7.810 % lower than the reference ratio, respectively. At 1100 s, the melting fraction of ratio 1 is 0.946, the melting fraction of ratio 0.6 is 0.998, and the melting fraction of ratio 0.5 is 0.992, which are

5.494 % and 4.863 % higher than the melting fraction of reference cross-cut ratio 1, respectively.



(a)



(b)

Fig. 3 (a) Melting fraction at different bottom cross-cut ratios; (b) Partial enlarged view of the third stage

B. Melting interface and velocity field

Fig. 4 shows the melt phase interface, velocity distribution and temperature distribution of different bottom cross-cut ratios tubes at 250 s, 500 s, 750 s and 1000 s, respectively. First of all, at 500 s, it can be seen that the areas of the liquid phase regions at different bottom cross-cut ratios are similar. This is because the phase change material is mainly in the solid phase, and the main heat transfer method is heat conduction. With the progress of the melting process, the liquid phase PCM gradually increases. The different areas are heated differently, resulting in a corresponding temperature gradient, making natural convection as the main heat transfer method. At 750 s, the lower the inclination, the lower the intensity of natural convection, which can be explained from the velocity at the interface of the melt phase. it can be seen from the color of the velocity field. The velocity at the molten phase interface is negatively related to the bottom cross-cut ratio. When the melting process develops to the 1000 s, the solid phase PCM areas are concentrated at the heat storage tube bottom. The larger bottom cross-cut ratio, the larger area of the tube bottom far away from the heating surface, the worse heat transfer effect, the longer complete melting time, and the more obvious refractory phenomenon at the bottom of the heat storage tube.

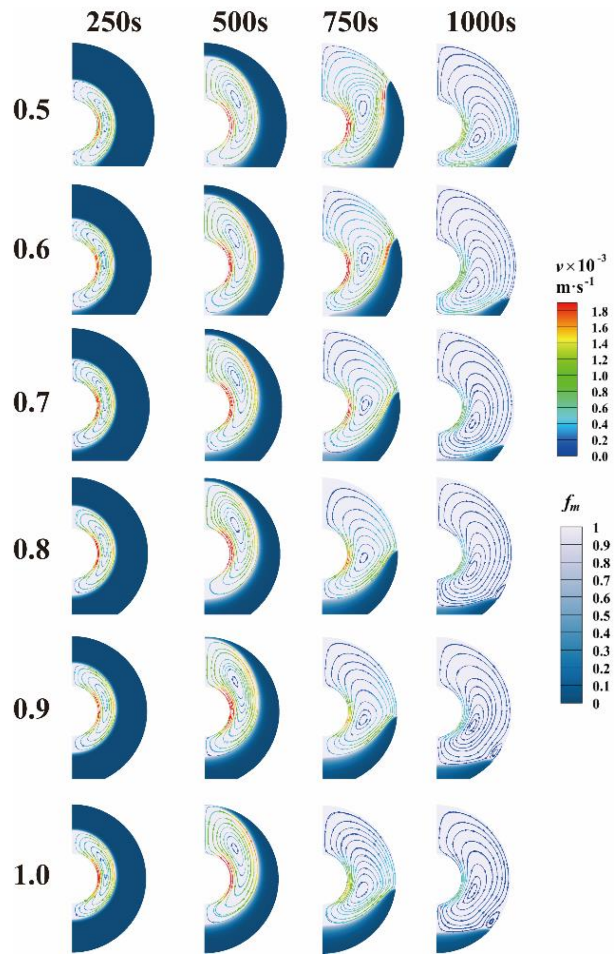


Fig. 4 Melt phase interface and velocity distribution at different bottom cross-cut ratios

IV. CONCLUSION

This paper studied the influence of the bottom cross-cut ratio to the horizontal LTHES unit, which has an obvious advantage to update the effective of energy storage. The transient melting behaviors including melting shape, liquid fraction, velocity fields were discussed.

(1) The closer the distance to the heating tube, the faster the heat conduction rate, the smaller the solid volume at the bottom of the heat storage tube.

(2) In terms of the overall melting rate trend, the smaller the bottom cross-cut ratio, the faster the melting rate. When the bottom cross-cut ratio is 0.6, the complete melting time is the least, 1120 s, which is 18.841 % shorter than that of the round tube. Thereby improving the overall melting efficiency.

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