Numerical study on thermal energy storage tube filled by metal foam with gradient porosities

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Abstract. Thermal energy storage has attracted more and more attentions due mainly to its ability of peak load shifting. Shell-and-tube configuration is a typical heat exchanger for thermal energy storage. To enhance phase change heat transfer, open-cell metal foam has been involved in various kinds of shell-and-tube heat exchangers. To further improve the overall thermal performance of a shell-and-tube heat exchanger, metal foams with gradient porosities were inserted into the shell side. Positive and negative gradients in porosity were studied for comparison. Numerical model was developed based on the finite volume method and three sets of numerical simulations were performed. Transient melting front and melting fraction were illustrated for comparison. Results demonstrated that the positive gradient in porosity outperformed the other two kinds of configurations, resulting in a 17.5% reduction in full melting time.

1. Introduction
Thermal energy storage is an effective way to solve the problem of uneven solar energy distribution, intermittent problems [1, 2]. Paraffin-based alkanes are a class of excellent phase change materials (PCMs), with superior characteristics of low cost, high latent heat and stable chemical properties. However, their low thermal conductivity limits the heat storage efficiency in real applications [3]. To improve the thermal performance, highly-conducting materials, e.g. metal foam is employed. Metal foam has high porosity and inter-connected porous structure with highly conducting ligaments [4, 5], favoring infiltrating PCMs for thermal energy storage. It has been demonstrated that metal foam can greatly enhance the effective thermal conductivity of PCMs [6-12]. Xiao et al. [13] introduced an infiltration method of fabricating composite PCM (metal foam/paraffin) and they tested several kinds of composite PCMs for thermal energy storage. Fleming et al. [14] experimentally studied that aluminum foam significantly enhanced the melting and solidification process by using aluminum foam. Yang et al. [2] both experimentally and numerically investigated the solidification process in metal foam composite PCM for cold storage and they found that metal foam can remarkably promote the interface evolution. Liu et al. [15] numerically studied the melting process in metal foam with a shell-and-tube unit, the phase change heat transfer can be enhanced more than seven times compared with pure PCM. For pore-scale observation on phase change process, volume-averaged method was recently compared with direct
numerical simulation on the melting behavior in copper foam-paraffin composite [16]. Results indicated that local natural convection in the melt phase contributed greatly to accelerate the melting front evolution. Most studies have focused on single-parameter foams, and only a few studies have shown that gradient design in pore parameters can further enhance melting heat transfer. Yang et al. [17] carried out the solidification experiment of distilled water in metal foam filled with gradient pore structures (porosity, pore density and parent material), and found that proper gradient design can further enhance the solidification heat transfer. For melting condition, a linear gradient in porosity can further improve the overall thermal performance [10]. Tao et al. also discovered that increasing the metal foam PPI(pore per inch) can enhance heat transfer, but weaken the natural convection.

Metal foam was widely used to enhance the thermal conductivity of phase change material and improve temperature distribution, to evaluate inner characteristics of heat storage tube is obviously crucial in the practical application. In this study, three types of heat storage tubes were examined with different porosity gradients. Numerical simulations were conducted, the melting front evolution was compared, at the same time, the melting fraction was calculated and analyzed.

2. Numerical simulation

Three sets of tubes were designed for studying the porosity gradient, as shown in Fig. 1. The heat storage tube was composed of an inner tube with an inner diameter of 20mm and a thickness of 1mm. The outer tube had a diameter of 90mm and the length of the whole tube was 270mm. Water was selected as heat transfer fluid and was injected from the top with a velocity of 0.01m/s and 70°C. The outer tube was filled with paraffin RT35 and copper foam. Heat storage tube was evenly divided into upper, middle and lower parts in the axial direction, as shown in Fig.1(b), (c) and (d). The three heat storage tubes are filled with copper foam of the same pore density (15 PPI) but different porosities. The upper, middle and lower portions of the tube 1 were filled with copper foam having a porosity of 0.94. The upper, middle and lower parts of tube 2 were filled with copper foam having a porosity of 0.90, 0.94 and 0.98, respectively; while the tube 3 were filled with copper foam having a porosity of 0.98, 0.94 and 0.90 from up to down. The average porosity of the three heat storage tubes was equal. Given the axial-symmetry feature, a 2D computational domain was built and commercial CFD software ANSYS-Fluent 18.2 was employed for solving the transient melting heat transfer with structural grids. The following results were all based on the simulation.

![Figure 1](image-url)

**Figure 1.** (a)Physical model for a shell-and-tube heat storage unit; 2D model with metal foams having porosities of (b) 0.94-0.94-0.94; (c) 0.90-0.94-0.98; (d) 0.98-0.94-0.94;
3. Results and Discussion

3.1. Melting Front

Figure 2 showed the melting fraction against time during thermal energy charging process for different copper foam tubes. The melting images could be divided into three parts: the blue and red parts were the solid and liquid phase, and the band between blue and red was in a mushy state. As time elapsed, more solid was melt and the melting front evolved deeply. The melting front was slant due mainly to the existence of local natural convection. Distinctive from the tube filled by uniform metal foam, the gradient design demonstrated different shapes for melting fronts. Tube 2 and tube 3 were filled with copper foams of three different porosities. From top to bottom, tube 1 was filled with metal foam with constant porosity of 0.94; tube 2 was filled with the ones with porosity of 0.90, 0.94 and 0.98; the sequence was the opposite for tube 3. However, the average porosity was the same 0.94 for the three tubes, indicating the same amount of PCMs for infiltration. It can be observed that the slant extent for tube 2 and 3 was different from the one for tube 1. It consumed less time for tube 3 for fully melting paraffin. The bottom region was greatly enhanced by introducing metal foam with a lower porosity. What’s more, in the early stage of heat storage process, compared with the heat storage process in the upper part of tube, tube 3 was much slowly. While with the advancement of heat storage process, the natural convection was highlighted, which accelerated the heat storage process. In the real design of heat transfer tube, it could be given full play to the positive effects of natural convection.

Figure 2. Melting front versus time for three tubes

3.2. Melting Fraction

Figure 3 illustrated the variations of liquid fraction as a function of time for the three tubes. During the initial heat storage for 500s, the melting curve change was relatively flat. After 500s of charging, the slope of the three curves increased rapidly and the melting fraction of tube 3 was the fastest than the other two tubes. After the charging process for 3000s, the difference of the melting rate curve between the tube 3 and the tube 1 was increased. Combined with the phase interface analysis, the remaining portion of the tube 1 at this time was mainly concentrated in the bottom part. With lower porosity in the bottom part for the tube, heat transfer was locally improved, which leaded to the overall phase change
improvement. Tube 3 completed the heat storage process after 4570 s, and the time required for the tubes 1 and 2 was 5540 s and 7570 s, respectively. Based on the heat storage time of the tube 1, the heat storage time of the tubes 3 was shortened by 17.5%, and the tube 2 was extended by 36.6%. It can be concluded that putting metal foam with a lower porosity at the bottom part can significantly enhance heat transfer. In addition, from the melting fraction curves of tubes 1 and 3, the degree of heat storage in the first 3000s is basically the same, combined with the phase interface analysis, the lower part of the tube 3 was in a molten state, then heat storage process of tube 3 speeded up, this phenomena also reflected the importance of natural convection in enhancing the heat transfer.

![Figure 3. Melting fraction versus time](image)

4. Conclusion

In this paper, the heat storage performances of three different heat storage tubes were simulated by a commercial CFD software ANSYS-Fluent 18.2. Under the premise of ensuring the heat storage effect of the three heat storage tubes, the distribution of copper foam porosity can be changed, which can shorten the heat storage time by 17.5%. According to the simulation results, it can be known that making full use of natural convection, ensuring the heat storage effect, and reducing the porosity of the porous media in the local part for tube can significantly shorten the heat storage time.

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