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NUMERICAL STUDY ON THE MELTING PERFORMANCE OF A THERMAL ENERGY STORAGE TUBE FILLED WITH METAL FOAM

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ABSTRACT

Thermal energy storage has been attracting more and more attentions due mainly to its distinctive features on peak-load shifting capability for systems with renewable energy involved. To further improve the overall thermal efficiency for charging/discharging processes, heat transfer techniques to enhance phase change heat transfer are typically employed. This paper introduced a novel concept of partially-filling ratio of metal foam into PCM. The melting heat transfer can be expected to be further enhanced with partially filled metal foams. To this aim, an axisymmetric two-dimensional computational model was established. A series of numerical simulations were carried out to study the effect of filling ratio of metal foam on the melting performance of a TES tube. Good agreement was achieved through the comparison of temperatures obtained from simulation and experimental measurements. Based on the results, it can be concluded as follows: if the goal was to enhance heat transfer simultaneously to save material cost, the suggested filling ratio was 0.90; if saving material cost was the aim, the filling ratio can be further reduced to 0.85. The proposed novel TES unit with partially-filled metal foam outperformed other competing heat transfer techniques, favoring a progressive potential in thermal energy storage applications.

Keywords: thermal energy storage, partially filling, porous media, numerical simulation, filling ratio

NONMENCLATURE

Abbreviations

CPCM	Composite phase change material
HTF	Heat transfer fluid
PCM	Phase change material
TES	Thermal energy storage

Symbols

f_m	Melting fraction
T	Temperature/K
t	Time/s
α	Filling ratio of metal foam
ε	Porosity

1. INTRODUCTION

Thermal energy storage can successfully meet the requirements of continuous energy supply in a solar energy utilization system [1]. As one competing technique, latent heat thermal energy storage has raised more and more attentions for solar energy utilization. Thermal energy is stored or released during charging or discharging processes with the help of phase change materials (PCMs). However, the inherently low thermal conductivity for PCMs, e.g. paraffin wax with a thermal conductivity of 0.2 $Wm^{-1}K^{-1}$ [2] may significantly lower the efficiency of thermal storage system. To this aim, plenty of studies have been conducted to improve the thermal efficiency of thermal energy storage system. By adding conducting fins [3], porous matrix [4] and nanoparticles [5] can effectively improve the phase change heat transfer. Compared with other competing structures, open-cell metal foam can not only accelerate the melting front evolution but also improve the temperature uniformity for PCM [6].

It was reported that the effective thermal conductivity of copper foam/paraffin composite was greatly increased [7]. Experimental measurements on the charging and discharging processes of copper foam/paraffin composite were performed by Meng et al. [8] and they claimed that metal foam can effectively improve the phase change heat transfer. Yang et al. [9] performed visualization of melting front in a TES unit filled with copper foam/paraffin composite. Atal et al. [10] experimentally found that a smaller porosity for metal foam can further greatly shorten the complete melting time. It was reported that the inclination angle of the copper foam/paraffin composite contributed little to the melting process, while it significantly affected the melting performance in a pure PCM [11]. Tao et al. [12] used lattice Boltzmann method to study the influence of porosity and pore density upon melting process of PCM saturated in metal foam.

Based on the aforementioned literature, it can be concluded that previous studies focused on the melting/solidification process in a TES tube with fully filled metal foam. The research progress confirmed the applicability and feasibility of filling metal foam into a TES tube to enhance phase change heat transfer. Recently, Xu et al. [13] partially filled the horizontal TES tube with metal foam and they suggested a filling ratio of 0.7 for maximizing the melting heat transfer. Inspired by their suggestions, we developed a vertical TES tube with partially filled by metal foam to further improve the thermal performance during melting process for thermal energy storage. To this aim, an axisymmetric two-dimensional computational model was developed and a series of numerical simulations were performed to study the effect of filling ratio on the melting rate of composite PCM.

2. NUMERICAL SIMULATION

Fig. 1(a) depicted the thermal energy storage tank considered in the present study. The TES tank was consisted of tube bundles where PCM embedded in metal foam, i.e. composite PCM (CPCM) was filled in the interstitial of the tube bundles and heat transfer fluid (HTF) was injected from top in the heat transfer tubes. For simplicity, only one heat transfer tube surrounded by CPCMs was considered, as shown in Fig. 1(b). With regard to the axisymmetric nature of circular tube configuration, an axisymmetric two-dimensional computational domain was established. Fig. 1(c) illustrated a TES tube with partially-filled by metal foam, where the top region was filled by pure PCM and the rest was filled by CPCM. HTF with a high temperature was injected from top in a constant velocity of 0.04 m/s to maintain a low Reynolds number less than 2300. The outlet was set as outflow and the left side was set as axis. The other sides were all thermally insulated.

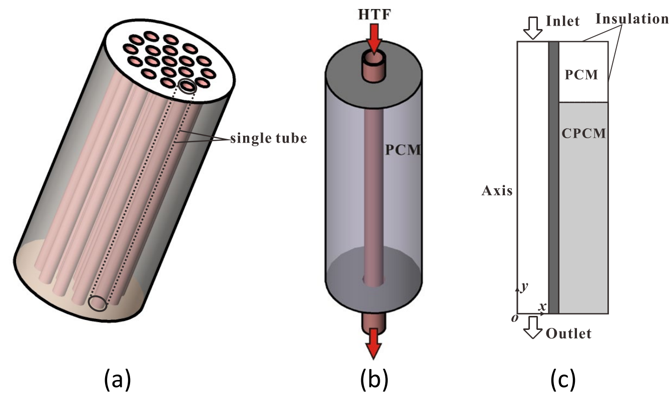

Fig 1 (a) Thermal energy storage tank; (b) Physical model; (c) Computational domain

ANSYS-Fluent 18.2 was used to simulate the melting process of CPCM in an TES tube. Conjugated heat transfer was modelled using the enthalpy method with incorporated by porous concept for the mushy zone in melting. ICEM 18.2 was used to generate grid for both PCM and HTF domains. The independence of grids was tested by three sets of grid densities and the time step sensitivity was also tested.

3. RESULTS AND DISCUSSION

3.1 Model verification

To validate the present numerical model, experimental results on temperatures at paraffin embedded in metal foam during melting process were employed for comparison. Fig. 2 demonstrated the comparison of temperatures on the ligament surface and the surrounded PCM. A reasonably good agreement can be found between numerical simulation and experimental results. This can be the proof of the feasibility and applicability of the built numerical simulation. The following discussions of results were all based on the verified simulation.

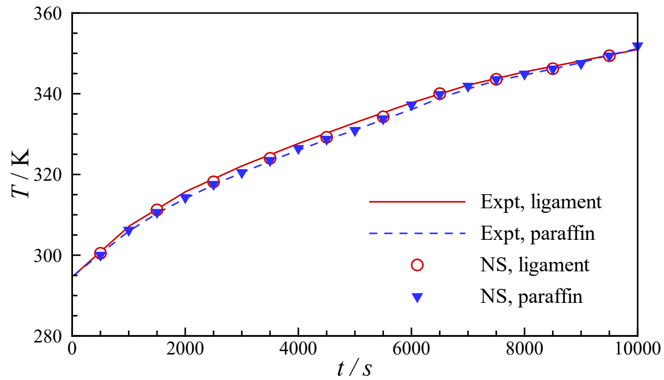

Fig 2 Validation of the numerical model: comparison with experimental results [14]

3.2 Melting fraction

Fig. 3 showed the melting fraction as a function of time for different filling ratios of metal foam. It can be observed that the melting fraction was in a monotonically increasing trend as time for all of the cases with different filling ratios. These results demonstrated the same variation trend: initially, the melting fraction increased in a slow speed; after the melting fraction was higher than 0.2, the increment trend was more rapidly; after the melting fraction reached 0.8, the increment speed for melting fraction was reduced again.

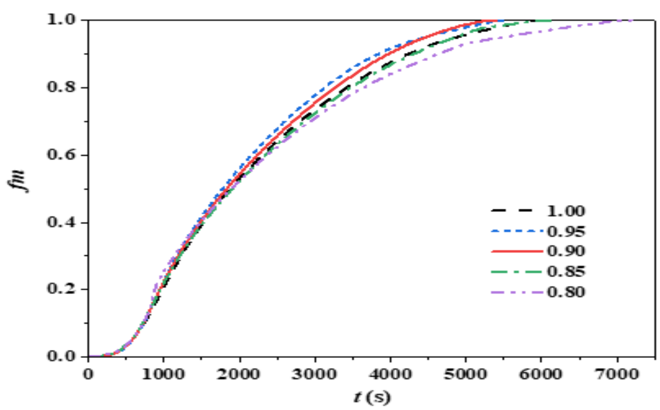

Fig 3 Melting fraction as a function of time for different filling ratios

An interesting phenomenon was observed that the melting speed did not increase with filling ratio. There existed an optimal filling ratio (0.90) to maximizing the melting fraction. This brought two benefits: i) the heat transfer can be further enhanced, reaching a higher melting fraction; ii) material cost can be further reduced with a 10% percent of saved metal foam. If using the same material for metal foam, i.e. the filling ratio of 0.85, a 15% percent of materials can be saved. This can be observed based on the fact that the melting curve for the case with partially filled ratio of 0.85 overlapped with the one fully filled by metal foam. With filling ratio further decreased to 0.80, the melting fraction decreased as well, indicating a lower heat transfer efficiency.

4. CONCLUSION

In this paper, a novel concept of partially-filling ratio of metal foam into PCM was developed. An axisymmetric two-dimensional computational model was established. A series of numerical simulations were carried out to study the effect of filling ratio of metal foam on the melting performance of a TES tube. Good agreement was achieved through the comparison of temperatures obtained from simulation and experimental measurements. Based on the results, it can be concluded as follows: if the goal was to enhance heat transfer simultaneously to save material cost, the suggested filling ratio was 0.90; if saving material cost was the aim, the filling ratio can be further reduced to 0.85.

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