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Experimental study on enhancement of thermal energy storage with phase-change material

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HIGHLIGHTS

- Experiments of phase change thermal energy storage enhanced by copper foam and fin were executed.
- Solid–liquid interface evaluation in radial direction was captured based on the shell-and-tube thermal energy storage cell.
- Solid–liquid interface evolutions for pure paraffin and copper foam composites with and without fin were recorded.
- Charging time, PCM temperature variation and heat transfer rate for all samples under various conditions were obtained.

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ABSTRACT

Latent heat thermal energy storage is a promising option for efficient utilization of intermitted and instable energy. However, the intrinsically low thermal conductivity of phase-change materials (PCMs) is the major shortage, leading to low energy charging and discharging rate. An experimental setup was designed to investigate the dynamic thermal behavior of a shell-and-tube latent heat thermal storage unit. Paraffin wax was employed as the PCM, of which the thermal properties, including that of melting temperature and latent heat, were detected by Differential Scanning Calorimetry. In order to improve the heat transfer performance, copper foam and a bottom fin were compounded to the PCM. High temperature water flowed through the copper tube as the heat transfer fluid (HTF). The temperature variations of the selected detected points inside PCM and the solid–liquid interface evolution in axial plane of symmetry for three samples, including that of pure paraffin, paraffin–copper foam composites without and with the bottom fin, were recorded under the different heating temperatures and flow rates of HTF. The experimental results indicate that completely melting the PCM in composite takes over 1/3 less time than that of pure paraffin under the same operating conditions. The total charging time consumption of the composite with a bottom fin is the least, as well as the heat transfer rate is the largest among the three samples. The influence of HTF temperature on the charging process is more significant than that of the HTF flow rate.

1. Introduction

As an effective approach to deal with the intermittency and instability of energy, latent heat thermal energy storage (LHTES) with phase change materials (PCMs) has great potential in many applications, such as concentrated solar power, energy-efficient building and waste heat utilization [1–3]. Compared with sensible heat thermal energy storage and chemical energy storage, the LHTES has several advantages, including that of high energy density, suitable phase change temperature, chemical stability and a reasonable price.

However, it is well known that most PCMs suffer from low thermal conductivity [4]. At present, the researches solve this problem mainly on two subjects, which are discovering more kinds of available PCMs and enhancing heat transfer to promote melting and solidification of the PCMs. Sharma et al. [5] and Zalba et al. [6] reviewed the development of thermal energy storage with solid–liquid phase change and listed hundreds of PCMs in research and industry. The PCMs selection for wide operating temperature ranged from 120 to 1000 °C [7], as well as their thermal performance analyses and the impregnation methods for compositions on basis of fluorides, chlorides, hydroxides, nitrates were also investigated [3,8]. On the other hand, strategies to enhance the heat transfer of PCM include but are not limited to (I) the utilization of extended

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Nomenclature

C	specific heat, J/kg °C
m	mass, kg
M	mass velocity of HTF, kg/s
Q	heat transfer rate, W
q	volume flow rate of HTF, m^3/h
T	temperature, °C
V	volume, m^3

Greek symbols

α	impregnation ratio
ε	porosity
ρ	density, kg/m^3

Subscripts

H	in thermostatic bath or high
HTF	heat transfer fluid
metal	metal foam
t	total mass/volume of test sample
i	inlet
o	outlet
PCM	phase change material
pore	pore of copper foam
molten	molten PCM

surfaces [9–12], (II) thermal conductivity enhancement to PCM [13–16], and (III) microencapsulation of PCM [17–19].

Radial fins are the most common type of the extended surfaces to enhance heat transfer, because of the simple structure and low manufacturing cost. Marcel [20] studied the melting process in a horizontal radial finned tube both experimentally and numerically. Chiu and Martin [12] and Zhao and Tan [21] analyzed a shell-and-tube latent heat storage unit with fins perpendicular to heating pipe. They used the same models with one placed in horizontal direction and the other in vertical direction, respectively. Tay et al. [22] compared the performances of pins and radial fins embedded on a tube. It was found that the radial fins on the tube had better performance than that of pins on the tube. A process of close-contact melting (CCM) in a vertical annular enclosure with radial finned inner tube was explored by Kozak et al. [23]. Their analytical model yielded the theoretical expressions for the time-dependent melt fraction, heat transfer rate and molten layer thickness in a dimensionless form.

Porous metal foam as an effective conductivity enhancement material also has been investigated extensively recently. Researches involving the open-cell metal foam were carried out from the four groups: the steady state calculation of effective thermal conductivity [24–27], the improvement of numerical method [28–34], the preparation of composite based on metal foam and PCM [35–37], and the thermal performance analysis of heat transfer enhancement with high conductivity metal foam [15,38–40]. The effective thermal conductivity is the key parameter for a composite of metal foam and PCM. Xiao et al. [25] prepared composites of copper foam and nickel foam with various porosities and pore sizes impregnated with pure paraffin. The effective thermal conductivity measured with steady-state method showed agreement with their theoretical predictions. Zhu et al. [27] put forward a novel method to calculate the thermal conductivity of aluminum foam based on the 3D reconstruction. The metal foam model was reconstructed by using the MATLAB image processing and CT scanning. The simulation technique of a solid–liquid phase change process in porous media had a rapid development in recent years. Nield and Bajan [30] reported a scaling analysis of PCM melting in porous matrix with the local thermal equilibrium method. They found that the melting phenomenon in porous media turned out to pass through four distinct regimes and each regime could be characterized by a distinct Nusselt number. Krishnan et al. [31] considered the difference in thermal diffusivities between metal foam and PCM. A two-temperature model was utilized to analyze both conduction and convection phenomena in porous media. Gao et al. [32,34] developed a lattice Boltzmann model for the melting with natural convection in porous media at the representative elementary volume scale. The local thermal equilibrium and non-equilibrium problems were both considered in their numerical models. Preparation of high impregnated ratio composites is important to widespread use of them. Sedeh et al. [37] simulated time-dependent evolution of liquid front during the pore-level infiltration of liquids into porous structures and obtained the influence of various driving forces including gravity, pressure gradient and interfacial effects to penetration process. Xiao et al. [35] prepared paraffin/nickel foam and paraffin/copper foam composites using a vacuum impregnation method. The thermal performance analysis of heat transfer enhancement for metal foam was carried out mainly by the numerical simulation. The experimental method was usually set as the validation. Chen et al. [33] studied the melting behavior of PCMs in metal foam at the pore scale experimentally and numerically. The results showed that conduction dominated the heat transfer mechanism in pore scale and natural convection exerted little influence on the melting process.

Regarding the experimental researches of using metal foam to enhance solid–liquid phase change, the literature review found that most investigations focused on the square cavity and under the condition of uniform heat flux boundary. These experiments could be simplified as two-dimensional problems and the purpose was primarily to provide validation for numerical simulations. It turned out that the shell-and-tube thermal energy storage system was commonly used. However, the experiments involving using metal foam to enhance the heat transfer performance were seldom investigated. In addition, the experiments for the shell-and-tube thermal energy storage with or without enhanced heat transfer technology only measured the time dependent temperature variations, while the interface evolution on axial plane of symmetry could not be captured at all. The interface on this plane is a significant performance index, which can intuitively reveal the effect of natural convection and show which part melts fast and which part does not melt in the charging process.

In our previous studies [38,41], LHTES enhanced by both metal foam and fins was analyzed by numerical method. In this study, an experimental setup was designed to test the thermal behavior of PCM under the effect of metal foam, as well as the combined effect of metal foam and a bottom fin based on the shell-and-tube TES unit. The symmetrical structure was extracted and used to acquire the visualized experimental results, as well as the solid–liquid interface development with time in axial plane of symmetry was recorded. High temperature water as the heat transfer fluid (HTF) flowed through a copper tube to heat the test samples. Under the same temperature and flow rate of the HTF, the dynamic thermal behavior for the pure PCM, paraffin–copper foam composite and paraffin–copper foam composite with a bottom fin was compared. The thermal characteristics including temperature profiles and position of solid–liquid interface were explored and recorded.