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Pore-scale visualization and measurement of paraffin melting in high porosity open-cell copper foam

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ABSTRACT

In this paper, a visualization and measurement investigation is performed on melting phase change of paraffin in high porosity open-cell copper foam at pore scale. With the aid of high definition camera and infrared camera, the phase and temperature fields of paraffin-foam and pure paraffin samples are captured to visualize the detailed melting phenomena. The local temperatures of both paraffin and copper foam matrix are measured by the thermocouples to study the thermal response characteristic and local thermal non-equilibrium effect. The experimental results reveal multiple pore-scale physical processes including the evolution of solid-liquid phase change interface, volume expansion of paraffin, motion of solid paraffin and release of air bubbles from paraffin. Under the combined influences of these physical processes, it shows that copper foam with a high porosity of 0.974 effectively extends the phase change interface and improves the thermal response rate of paraffin. As a result, the melting rate of paraffin has increased by more than two times, while the reduction in the amount of latent heat is only 2.6%. Moreover, significant effect of local thermal non-equilibrium between paraffin and copper foam is found during the melting process of paraffin-copper foam sample. Finally, through generalizing results from present experimental measurements, a correlation for dimensionless melting time of the paraffin-copper foam sample at pore scale is developed. The present investigation can contribute to a better understanding of melting in metal foam and provide guidance for the application and performance analysis of paraffin/metal foam composite.

1. Introduction

In recent years, there is an urgent need for the high efficiency utilization of the thermal energy resources as the serious energy crisis impedes the industrial and economic development. In this situation, the solid-liquid phase change materials (PCMs) with a high latent heat and nearly constant phase change temperature have been widely utilized in many applications (such as thermal energy storage of intermittent heat sources [1–4] and thermal management of high-power electronic devices [5,6], etc.) to improve the energy efficiencies. However, the PCMs (such as paraffin) suffer from problems of low thermal conductivity (around 0.2 W/(m·K)) and existence of air cavities, which increase the heat transfer resistance and prolong the heat charging/discharging periods [7,8]. To overcome this limitation, a variety of heat transfer enhancers including highly conductive metal fins [9–11], nanoparticles [12,13], carbon nanofibers [14] and high porosity open-cell metal foams [15–17] are employed. Among these heat transfer enhancers, the high porosity open-cell metal foam is found to be especially effective in improving the performance of PCM because of its high thermal conductivity, large surface area to volume ratio, highly interconnected structure and fluid mixing effect. Due to the wide application of paraffin/metal foam composite [18–25], the phase change characteristics of PCMs in metal foams have attracted increasing research attention.

Lafdi et al. [18] carried out an experimental study on the melting heat transfer characteristics of PCM inside aluminum foams, in which the temperature field was measured and the evolution of solid-liquid phase change interface was captured. It showed that the heat transfer behavior of the PCM/foam composite was significantly influenced by foam porosity and pore size. Siahpush et al. [19] experimentally evaluated the performance enhancement of a cylinder latent heat thermal energy storage system with copper foam as heat transfer enhancer. It was found that the copper foam

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Nomenclature

c_p	specific heat [J kg^{-1} K^{-1}]
Fo	Fourier number (dimensionless melting time) [−]
g	gravitational acceleration [m^2 s^{-1}]
h	height of test sample cross section [m]
K	permeability [m^2]
k	thermal conductivity [W m^{-1} K^{-1}]
L	latent heat [kJ kg^{-1}]
l	length of test sample cross section [m]
m	mass [kg]
Ra	Rayleigh number [−]
Ste	Stefan number [−]
T	temperature [°C]
ΔT	temperature difference [°C]
t	time [s]
V	volume [m^3]
y	Cartesian coordinate [m]

Greek symbols

α	thermal diffusivity [m^2 s^{-1}]
β	volumetric expansion coefficient [K^{-1}]
ε	porosity [−]
μ	dynamic viscosity [Pa s]
ρ	density [kg m^{-3}]

Subscripts

eff	effective
l	liquid
m	melting
mf	metal foam
mt	melting time
s	solid
w	heating wall

obviously reduced the time required for both melting and solidification phase change processes. Dukhan and Bodke [20] performed experiments to study the heat transfer in a cubic block of aluminum foam saturated with paraffin. Their results showed the significant enhancements of phase change rate and temperature uniformity due to the adoption of the highly conductive aluminum foam. Zhao et al. [21] experimentally investigated the solid-liquid phase change inside rectangular copper foams saturated with paraffin. They found that the overall heat transfer rate can be increased by 3–10 times depending on foam structure parameters. Li et al. [22] experimentally studied the melting phase change in copper foams saturated with paraffin, in which the effects of heat diffusion and natural convection were examined. It showed that the improvement of heat diffusion was more prominent than the depression of natural convection of liquid paraffin caused by copper foam matrix. Baby and Balaji [23] performed an experimental investigation on the thermal performance of PCM-copper foam based heat sink. The results indicated that the heat transfer capacity of PCM-metal foam combination was attractive for the cooling applications. Mancin et al. [24] experimentally studied the phase change phenomenon in copper foams. They found that the onset of the melting process with copper foams was delayed but it ended earlier than the pure paraffin case. Zhang et al. [25] measured the melting characteristics of paraffin/copper foam composite. It was revealed that the thermal non-equilibrium effect between foam matrix and paraffin was evident.

Besides the above experimental investigations, a number of theoretical studies concerning solid-liquid phase change of PCM inside open-cell metal foams had been carried out. Krishnan et al. [26] proposed a 2D thermal non-equilibrium model for solid-liquid phase change in open-cell metal foams based on the volume averaging method at the macroscopic scale. The influences of Rayleigh number, Stefan number and Nusselt number on the phase change interface evolution and melting rate were investigated. However, this study roughly estimated the effective thermal conductivity (ETC) of metal foam saturated with PCM through volume averaging method without considering the influence of foam structure. Yang and Garimella [27] proposed a 2D thermal non-equilibrium model to study the melting of PCM in open-cell metal foam, and the effect of foam structure on the ETC was considered based on empirical correlations. Li et al. [22] and Tian and Zhao [28] developed 2D heat transfer models considering the thermal non-equilibrium effect for PCMs embedded in metal foams, in which the thermal dispersion effect due to fluid mixing by foam matrix was considered. Liu et al. [29] and Nithyanandam and Pitchumani [30] respectively developed 3D thermal non-equilibrium models for phase change of PCM-filled metal foams, and they both employed the 3D models for the performance analysis of different latent heat thermal energy storage systems. In addition to these thermal non-equilibrium models, some relatively simpler models with an assumption of thermal equilibrium between PCM and metal foam were presented in Refs. [17,31], which should be discreetly adopted because the thermal non-equilibrium effect can be evident during the real solid-liquid phase change process inside metal foam [25].

It should be noted that all the aforementioned experimental studies mainly focused on the measuring of the volume-averaged performance of PCM-foam samples at the macroscopic scale. The sample dimension was much larger than the foam pore size and the local information of heat transfer and fluid flow in foam pore space during phase change process was usually neglected in these works. In addition, the above theoretical models, which were developed for the macroscopic scale analysis based on the volume averaging technique, inherently ignored the small details of phase change phenomena in the foam pore region for ease of analysis.

Compared to the macroscopic scale study, the pore-scale investigation on solid-liquid phase change in metal foam can better reveal the phase change mechanism by considering small details of the transport processes in foam pore region. By now, only a few works have been reported at the pore-scale level. Hu and Patnaik [32] and Sundarram and Li [33] numerically modeled the phase change heat transfer of PCM inside open-cell metal foams at pore scale by adopting 3D body-centered-cubic (BCC) foam cell and 3D face-centered-cubic (FCC) foam cell, respectively. Chen et al. [34] experimentally and numerically studied the melting of PCM in open-cell metal foams at pore scale, in which the numerical work was focused on 2D melting of PCM in foam pore region. Feng et al. [35] studied the melting process of PCM infiltrated in a finned metal foam at pore scale by constructing a 3D sphere-centered tetrakaidecahedron foam cell. These pore-scale studies can reveal the evolution of the solid-liquid phase change interface in the foam pore, which was ignored by the experimental measurements and the theoretical analyses at the macroscopic scale. Nevertheless, it should be pointed out that all above pore-scale studies neglected the volume change of PCMs (note that the PCMs can have a volume change greater than 10% during phase change process) and the