International Journal of Thermal Sciences 135 (2019) 94–103

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

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

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ARTICLE INFO

Keywords:
Solidification phase change
Visualization and measurement
Metal foam
Pore scale
Volume shrinkage
Local thermal non-equilibrium

ABSTRACT

In this work, a pore-scale experimental investigation on solidification of paraffin in high porosity open-cell copper foam is performed based on the visualization and measurement technique. With the use of high definition camera and infrared camera, the phase and temperature fields of the copper foam/paraffin sample are obtained to directly visualize the solidification process. Simultaneously, T-type thermocouples are employed to measure the local thermal response characteristic and thermal non-equilibrium effect of the copper foam/paraffin sample. For comparison, the corresponding solidification experiment with pure paraffin sample is also conducted. Local details of solidification phase change including the evolution of phase change interface within foam pore region, the liquid phase flow and air gap formation due to the volume shrinkage effect of paraffin are revealed. It is found that the highly conductive copper foam remarkably extends the phase change interface, avoids the formation of overlarge-size air gap that forms in the pure paraffin sample and enables a higher thermal response rate of the copper foam/paraffin sample. As a result, an attractive solidification enhancement (about 2.8 times) of paraffin in copper foam is achieved. Moreover, strong effect of local thermal non-equilibrium between copper foam and paraffin is detected during the solidification process. Finally, through generalizing the present experimental results, a correlation for dimensionless solidification time of the copper foam/paraffin sample is developed at pore scale.

1. Introduction

High porosity open-cell metal foam/paraffin composite (MFPC), which combines the outstanding heat transfer performance of metal foam [1–8] with the solid-liquid phase change property of paraffin [9–14], has great value to improve the energy efficiency in various applications, such as industrial waste heat recovery [15,16], solar energy storage [17,18], electronics cooling and thermal management of Li-ion batteries [19–22]. The design, performance evaluation and practical application of MFPC require the scientific cognition on the phenomena, behaviors and characteristics related to the melting and solidification of paraffin in porous metal foam, which thus has attracted increasing research attentions over the past decade.

A great number of investigations on the melting and solidification phase change of paraffin in metal foam have been performed at the macroscopic scale, which mainly focused on the volume-averaged phase change behavior and performance of MFPC. It is noticed that Lafdi et al. [23] made a pioneering work concerning measurement and visualization of paraffin melting in aluminum foams with different porosities and pore sizes. The results showed that the thermal diffusion and convection in aluminum foam/paraffin composite were strongly related to foam porosity and pore size, which together determined the solid-liquid phase change interface of paraffin. Then, Siahpush et al. [24] measured both melting and solidification of paraffin in copper foam, and they found that the copper foam largely reduced the times required for the phase change processes of paraffin. Furtherly, Dukhan and Bodke [19], Zhao et al. [25], Baby and Balaji [20], Mancin et al. [26] and Hussain et al. [21] experimentally examined the phase change behaviors of MFPCs employed in various heat storage and thermal management devices. It was revealed that excellent thermal performances of these energy devices were achieved due to the phase change advantage of paraffin in metal foam. Through developing transport models based on volume-averaging theory of porous media, the phase change of paraffin in metal foam has also been investigated numerically. Zhao et al. [25] and Li et al. [27] simulated paraffin melting in metal foam by developed 2D transport models, which followed an earlier 2D model for the solid-liquid phase change in metal foam-based porous media proposed by Krishnan et al. [28]. Besides, Liu et al. [29]

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https://doi.org/10.1016/j.ijthermalsci.2018.09.007
Received 7 March 2018; Received in revised form 10 August 2018; Accepted 4 September 2018

Nomenclature

c_p	specific heat [J kg^{-1} K^{-1}]
Fo	Fourier number (dimensionless solidification time) [−]
g	gravitational acceleration [m^2 s^{-1}]
h	height of test sample cross section [m]
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]
Q	heat [J]
Ste	Stefan number [−]
T	temperature [°C]
ΔT	temperature difference [°C]
t	time [s]
U	experimental uncertainty [−]
V	volume [m^3]
Y	Cartesian coordinate [m]

Greek symbols

α	thermal diffusivity [m^2 s^{-1}]
δ	uncertainty symbol [−]
ε	porosity [−]
ρ	density [kg m^{-3}]

Subscripts

ave	average
c	copper
eff	effective
in	initial
ir	infrared camera
l	liquid
loss	heat loss
m	mean
mf	metal foam
p	paraffin
s	solid/solidification point
st	solidification time
sty	styrofoam
T	total
tc	thermocouple
w	cooling wall

and Srivatsa et al. [30] proposed 3D transport models to numerically predict the phase change of MFPC in a shell-and-tube type latent heat thermal energy storage system and a heat sink, respectively. These numerical works presented additional phase change information including the velocity and liquid fraction distributions of paraffin in metal foam that were not measurable in above experimental studies.

To gain further insights into the phase change physics of paraffin in metal foam and provide guidance for the application and modeling of MFPC in both small and larger scale energy systems, the corresponding pore-scale investigations that consider local details of transport processes in pore region of metal foam have received great importance and interests nowadays. Sundarram and Li [31] made a numerical study of paraffin melting in aluminum foams at pore scale by neglecting natural convection of liquid paraffin, in which the effects of foam porosity and pore size under different thermal boundary conditions were explored. It was shown that the performance of solid-liquid phase change in metal foam was closely associated with both porosity and pore size. Feng et al. [32] numerically investigated the pore-scale melting phase change of paraffin in aluminum foam considering the natural convection of liquid paraffin, and it was found that the melting process was accelerated by the natural convection of liquid paraffin within foam pores. Yao et al. [33,34] performed pore-scale numerical studies on the heat conduction and interstitial heat transfer characteristics of MFPC having different foam porosity and pore size at pore scale, in which the effective thermal conductivity and interstitial heat transfer coefficient of MFPC serving as crucial thermophysical parameters for modeling the phase change of paraffin in metal foam were determined. Chen et al. [35] experimentally examined the melting phase change evolution of paraffin in aluminum foam at pore scale. They found that the melting of MFPC was mainly affected by the heat conduction of metal matrix, and the local thermal non-equilibrium effect of MFPC was significant. Jin et al. [36] carried out a pore-scale experimental investigation on paraffin melting in copper foam through visualization method addressing emphatically the effect of pore size. Results indicated that the copper foam/paraffin composite with smaller foam pores owned a more desirable thermal performance. Most recently, Yao et al. [37] performed pore-scale measurement and visualization on paraffin melting in copper foam, in which they discussed the phase change behaviors concerning paraffin volume expansion and air bubble release in the pore region of copper foam that were often ignored in previous studies. It is worth pointing out that although by now many pore-scale investigations have been made on the aspect of phase change of MFPC, the solidification phase change of MFPC has still not been explored at pore scale to the best of our knowledge. As results, the basic issues such as the local evolution of phase change interface, influence of paraffin volume variation, thermal response characteristic of individual phase and effect of local thermal non-equilibrium corresponding to solidification of paraffin in metal foam are not clear. Considering these issues that are of vital importance to more completely understand the phase change process of MFPC and provide physical basis for the application and modeling of MFPC, the solidification of paraffin in metal foam is highly required to be researched at pore scale at present.

Therefore, the objective of the present work is to experimentally investigate the solidification phase change of paraffin in a high porosity open-cell copper foam at pore scale. By comprehensively employing the high definition camera, infrared camera and thermocouples, the detailed solidification phenomena and behaviors of both copper foam/paraffin sample and pure paraffin sample are visualized, measured and compared. The corresponding thermal response characteristic, effect of local thermal non-equilibrium and solidification strengthening performance of the copper foam/paraffin sample are revealed. Furtherly, based on the present experiment, a correlation for dimensionless solidification time of the copper foam/paraffin sample is proposed at pore scale.

Fig. 1. Sample of copper foam.