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Effective thermal conductivity of open-cell metal foams impregnated with pure paraffin for latent heat storage

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A B S T R A C T

The thermal conductivity of phase change material (PCM) significantly affects the thermal performance of latent heat thermal energy storage (LHTES) system, which is attractive for energy conservation and waste heat utilization. Metal foam can be applied to enhance the low thermal conductivity of pure PCM. In the present study, copper foam and nickel foam with various porosities and pore sizes were impregnated with pure paraffin with vacuum assistance. A steady-state test system which considered the thermal contact resistance (TCR) between the specimen and adjacent surfaces was constructed to measure the effective thermal conductivities of the composite PCMs. The thermal conductivities were also theoretically calculated based on the correlations and models from the literature. The results showed that the thermal conductivities measured with steady-state method showed good agreement with the theoretical predictions, and the thermal conductivities of the composite PCMs were drastically enhanced, e.g., the thermal conductivities of the paraffin/copper foam composite PCMs fabricated by the copper foams with the porosities of 96.95%, 92.31%, 88.89% and pore size of 25 PPI were about thirteen, thirty-one, forty-four times larger than that of pure paraffin, respectively. The ratios of TCR to the total thermal resistances of the composite PCMs with the thickness of about 20.0 mm were in the ranges of 15.0−50.0%.

1. Introduction

The energy crisis becomes a critical issue nowadays and a great many of techniques are implemented to improve the energy efficiency. Energy storage is a useful method to alleviate the mismatch between energy supply and demand. Latent heat thermal energy storage (LHTES) with large energy storage density and isothermal heat storage/retrieval characteristics has been a hot research topic for energy conservation and waste heat utilization [1,2]. However, the low thermal conductivity of phase change material (PCM) generally below 0.4 W/(m K) significantly degrades the thermal performance of the LHTES system. Thus various methods have been proposed to enhance the thermal conductivity of PCM [3]. Open-cell metal foams with attractive mechanical property, ultra-low relative density, and high thermal conductivity for continuous skeleton structure, can be applied to enhance the thermal conductivity of pure PCM. Consequently, the composite PCMs fabricated by porous metal foams and pure PCMs can be applied to many situations, such as LHTES system [4,5], heat sink [6], heat exchanger [7,8], and so on.

The accurate information of the effective thermal conductivity of the metal foam or composite PCM is essential to design and model the LHTES system, which have been investigated theoretically and experimentally. A variety of theoretical models were proposed to predict the effective thermal conductivities of metal foams [9−15]. Calmidi and Mahajan [9] proposed a unit cell model of hexagonal structure with the square intersection to estimate the effective thermal conductivities of metal foams. Bhattacharya et al. [10] extended the unit cell model of hexagonal structure with the circular intersection to estimate the effective thermal conductivities of metal foams. In addition, three-dimensional models were also used to estimate the effective thermal conductivities of metal foams saturated with or without fluids, such as the cubic lattice model [11], the tetrakaidecahedron cell model [12,13] and other models. Bai et al. [14] built a simplified model based on diamond-shaped unit cells to predict the heat transfer enhancement of a channel filled with metal foam. Bodla et al. [15] conducted an image-based analysis to predict the effective thermal conductivities

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Nomenclature

A	cross-sectional area (m^2)
a_{sf}	interfacial surface area (m^{-1})
B	parameter in correlation of Bhattacharya et al. in Table 3 (–)
b/L	length ratio in model of Calmidi and Mahajan in Table 3 (–)
C	length ratio in model of Boomsma and Poulikakos in Table 3 (–)
d	diameter (m)
d_f	fiber diameter (m)
d_p	pore size (m)
e	parameter in model of Boomsma and Poulikakos in Table 3 (–)
F	parameter in correlation of Singh and Kasana in Table 3 (–)
h	thickness (m)
I	current (A)
m	mass (kg)
R	thermal resistance (K/W)
ΔR	thermal resistance difference (K/W)
T	temperature (°C)
ΔT	temperature difference (°C)
t	dimensionless thickness of solid skeleton in Table 3(–)
Q	heat flow (W)
$\overline{Q}$	mean heat flow (W)
r	area ratio in Table 3 (–)
U	voltage (V)
V	volume (m^3)
x	distance (m)
x_s	thermal conductivity ratio in Table 3 (–)

Greek symbols

α	impregnation ratio (–)
δ	volume shrinkage ratio in Table 3 (–)
ε	bulk porosity (–)
ζ	length ratio of the edge of the cavity to the outer edge of the pore in Table 3 (–)
λ	thermal conductivity (W/(m K))
ξ	length ratio of the inner edge of the skeleton to the outer edge of the pore in Table 3 (–)
ρ	density (kg/m^3)
ω	pore density (pore per inch, PPI)

Subscripts

cp	composite PCM
e	effective value
fo	foam
l	lower
s	solid state
st	stainless steel
sk	metal skeleton
t	total
tk	thick
tn	thin
u	upper

of metal foams. Furthermore, numerical calculation was applied to estimate the effective thermal conductivities of highly porous metal foams [16]. Moreover, experimental measurement is indispensable to validate the theoretical models. Transient methods including laser flash method [17] and transient plane heat source technique (TPS) [18,19] have been used broadly for the convenient operation. However, the surface roughness of the specimen greatly influences the measurement accuracy because the thermal contact resistance (TCR) between the specimen and sensor presents in the measurement. Furthermore, the anisotropic characteristic of the composite PCM is very apparent because the thermal conductivity of metal skeleton is much larger than that of pure PCM. As a result, the measurement results of the effective thermal conductivities may have large uncertainties and deviations case by case. Conventional steady-state method as a promising method was used to measure the effective thermal conductivities of metal foams [9,10,12,20] and composite PCMs [21,22]. The experimental setups were constructed and the metal foams were placed between the hot and cold plates, then the effective thermal conductivities of metal foams or metal foams saturated with air or water were determined under the steady-state conditions [9,10,12,20]. Sedeh and Khodadadi [21] measured the temperature distribution within the cyclohexane/graphite foam composite when the heat flux was applied on the bottom wall, and the effective thermal conductivity was evaluated with the temperature gradient at the steady-state. Hong and Herling [22] investigated the effects of geometric parameters (pore size and specific surface area) of open-cell aluminum foams on the effective thermal conductivities of the paraffin/aluminum foam composites, which were determined by the temperature difference of temperature evolution at the steady-state. Moreover, it can be seen that all the aforementioned measurements with steady methods always neglected the TCRs between the specimen and fluxmeters, which might cause large uncertainties for the measuring results. TCR is an important parameter and has been studied by several researchers previously [23–25]. Kamath et al. [23] investigated the heat transfer performance of a vertical channel filled with open-cell metal foams and used a simple thermal resistance model to estimate the TCR between all the surfaces that were in contact. Their results revealed that the presence of the TCR played a key role in the reduction of the Nusselt number in the mixed convection regime. Fiedler et al. [24] numerically and experimentally analyzed the thermal resistance of porous foam, and pointed out that the measured resistances included the conductive resistance and TCR. Sadeghi et al. [25] measured the effective thermal conductivities as well as the TCRs in a vacuum chamber under different prestressing loads for aluminum foams with various porosities and pore sizes. Their results showed that the TCR accounted for an important portion in the whole thermal resistance, and the TCR decreased significantly with pressure due to an increase in the real contact area at the interface.

It can be seen that the aforementioned investigations only provided initial insight of the TCR for metal foams. The distinguishing of the TCR and effective thermal conductivity of the PCM/metal foam composite PCM during the measurement is not studied yet, which is quite important for determining the accurate information of the effective thermal conductivities of the composite PCMs and their applications in the LHTES system. In a previous study [26], pure paraffin with desirable properties [27,28] was selected as the PCM, and metal foams were selected as the porous material for thermal conductivity enhancement. The morphological characterizations of the nickel and copper foams with high porosity (>95%), such as the surface porosity and bulk porosity, were studied. Impregnation ratios were studied comparatively for the