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Thermal performance of copper foam/paraffin composite phase change material

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ABSTRACT

Phase change materials are promising options for thermal energy storage and thermal energy devices. However, their low thermal conductivity lowers their charging and discharging rate. In this paper, copper foam was utilized to enhance the thermal performance of the paraffin. A visible experimental device was built to investigate the melting behavior of paraffin with and without copper foam. The effect of the heating position on the thermal performance of copper foam/paraffin composite phase change material (CPCM) was also discussed. The heat transfer characteristics including solid-liquid interface development, temperature distribution and wall temperature of the heater were tested and recorded. In addition, a numerical model was established using one-temperature volume averaging method to analyze the melting process of the CPCM. The experimental results showed that the total melting time of the CPCM was 20.5% shorter than that of pure paraffin, and the CPCM heated at the top melted slowest and reached the biggest temperature difference in the three heating conditions, so the effect of natural convection on the melting process of the CPCM could not be neglected. A two dimensional numerical simulation was also performed to analyze the melting behavior of CPCM, and the numerical results were well consistent with the experimental data.

1. Introduction

Phase change materials (PCMs) have been extensively utilized in the fields of thermal energy storage and electronic thermal management due to their high enthalpy of phase change, suitable and constant phase change temperature, stable chemical property and low cost [1,2]. However, a major drawback of PCMs is their low thermal conductivity, which reduces their heat transfer rate and hampers their further application in many fields [3,4]. In order to improve their thermal performance, many methods have been used to enhance their thermal conductivity, including installing metal fins [5,6], adding heat pipes [7,8],dispersing highly conductive nanoparticles [9,10], as well as embedding PCM in expanded graphite [11,12] or metal foam [13,14]. Among these techniques, adding metal foam appears to be more efficient to improve the thermal conductivity because of its high surface area, high porosity, high thermal conductivity, high strength, and light weight.

A number of studies on application of metal foam with PCM have been conducted by utilizing experimental and numerical methods. In relation to experimental method of metal foam/ PCM composite, Xiao et al. [15] fabricated copper foam/paraffin composite PCM using the method of vacuum impregnation and employed transient plane heat source technique to measure the thermal conductivity of the composite. They found that the composite had a thermal conductivity about 15 time higher that of pure paraffin. Cui [16] filled paraffin in copper foam, and the temperature distribution and heat transfer rate of the composite were investigated. The experimental results indicated that the addition of copper foam can result in a more uniform temperature distribution in the paraffin and significantly shorten the charging time. Mancin et al. [17] applied paraffin as PCM and copper foams with the same porosity and various pore sizes as the heat transfer enhancer. The authors found that the use of the copper foam can extensively improve heat transfer properties of the paraffin and pore size of the copper foam did not have any remarkable effect on the heat transfer performance of the paraffin. Yang et al. [18] employed high temperature water to heat pure paraffin and copper foam/paraffin composite PCM. The temperature distribution and evolution of the solid–liquid interface of PCM were obtained and discussed. They concluded that the composite owned significantly faster melting rate because of its higher thermal conductivity, and the influence of water temperature on the charging process was more significant than that of the water flow rate. Li et al. [19] experimentally evaluated the thermal performance of

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Nomenclature

A_m	constant parameter
C	inertial coefficient (1/m)
c_p	specific heat capacity (J/(kg·K))
g	gravitational acceleration (m/s^2)
K	permeability (m^2)
k	thermal conductivity (W/(m·K))
L	latent heat (J/kg)
P	power input (W)
p	pressure (pa)
S	source term
T	temperature (K)
T_0	initial temperature (K)
T_{m1}	onset melting temperature (K)
T_{m2}	melted temperature (K)
t	time (s)
u, v	velocity in x, y directions (m/s)

Greek symbols

β	liquid fraction in pore
γ	thermal expansion coefficient (1/K)
δ	liquid fraction
ε	porosity
μ	dynamic viscosity (kg/(m·s))
ρ	density (kg/m^3)
ω	constant parameter

Subscripts

f	paraffin
s	copper foam
eff	effective value

microencapsulated PCM/ copper foam composite. The results showed that the addition of metal foam had lowered the surface temperature by maximum 47% and unified the internal temperatures in the composite ascribed to the enhancement of thermal conductivity by metal foam.

Considering numerical simulation, Tian et al. [20] conducted numerical investigation into the effect of copper foam on the enhancement in paraffin utilizing the two-equation non-equilibrium heat transfer model. The results showed that the copper foam with smaller porosity provided better heat transfer performance than that with larger porosity because the former possessed more solid skeleton to transfer heat flux into paraffin. Li et al. [21] carried out a numerical simulation considering the non-Darcy effect and local natural convection to explore the thermal characteristics of copper foam/paraffin composite PCM and assumed local thermal non-equilibrium between copper foam and paraffin. They found that thermal resistance of the composite was lower than that of pure paraffin, and natural convection is the dominate heat transfer mechanism of the melting process. Besides, the results also validated the feasibility and necessity of the local thermal non-equilibrium model used in this field. Chen et al. [22] adopted a thermal lattice Boltzmann model with doubled populations to investigate the melting process of paraffin in aluminum foam. The results indicated that heat conduction in metal fiber made a great contribution to the melting of paraffin, and nature convection in the composite was weakened due to the increase of flow resistance in aluminum foam. Hu et al. [23] performed direct numerical simulation to study complicated heat transfer behavior of aluminum foam/paraffin and compared the results with those from one- temperature and two-temperature volume-averaged simulations. They found that two-temperature volume averaged simulations provide a more reasonable prediction to the heat transfer process of paraffin in metal foam. Zhang et al. [24] established an intricate three dimensional porous medium investigate the heat transfer process of PCM infiltrated in metal foams with a porosity gradient. The results indicated the metal foam with a porosity gradient increased the heat storage rate by enhancing the melting process at the corner of the bottom region.

Considering the literature review, it can be concluded that most researches regarding PCM embedded in open-cell metal foam focused on four aspects: effective thermal conductivity of the composite PCM, the thermal performance and mechanisms analysis of utilizing highly conductive metal foam as heat transfer enhancer, the improvement of simulation model, method to fabricate the composite. To the authors'-knowledge, Few studies were carried out to investigate the effect of heating position on the thermal behavior of the copper foam/paraffin composite phase change material (CPCM). In the present study, a visible experimental device was built to investigate the melting behavior of paraffin with and without copper foam, and the effect of heating position on the thermal behavior of CPCM. The thermal performance of the CPCM heated on the left, at the bottom and at the top, respectively, was discussed through recording primary heat transfer characteristics including solid-liquid interface development, temperature distribution, wall temperature of the heater, and completely melted time. In addition, a numerical model considering the effective thermal conductivity of the CPCM was also established using volume averaging method based on single-domain energy equation to analyze the melting process of CPCM, the liquid fraction and temperature contours of CPCM were recorded, and the simulation results was compared and validated with experimental data.

2. Experiment

2.1. Experiment material

Copper foam with the porosity of 0.95 and the pore size of 5 PPI utilized in the melting experiment is shown in Fig. 1, which was provided by Suzhou JYS metal foam Co. Ltd. Industrial grade paraffin was purchased from Sinopharm Chemical Reagent Co. Ltd. Since various paraffin possessed different melting point and latent heat that are important thermal properties, the melting point and latent heat of paraffin were detected on a Differential Scanning Calorimeter (DSC) owning a cooling system and the operating temperature ranged from 20 to 80 °C

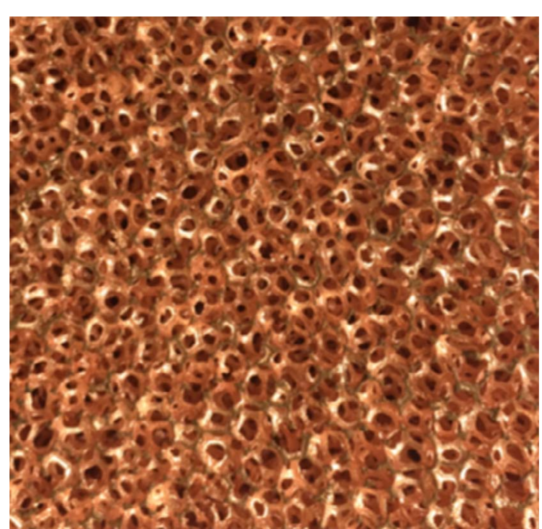

Fig. 1. Copper foam.