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Research Paper

Numerical analysis and comparison of the thermal performance enhancement methods for metal foam/phase change material composite

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HIGHLIGHTS

- Three methods to improve the melting rate of phase change material embedded in metal foam are investigated and compared.
- The metal foam with small pore size could enhance the heat transfer of the composite.
- The modified shape of the container is beneficial to the natural convection during the phase transition process.
- An optimized method is proposed by combining the advantages of two methods.

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ABSTRACT

Three methods to further enhance thermal performance of the metal foam/phase change material (PCM) composite are investigated and compared. These three methods include changing the pores per inch (PPI) of metal foam, modifying the shape of the cold wall and using the discrete heat sources. In this study, the composite consists of two materials: aluminum foam with 90% porosity as metal foam and paraffin wax as PCM. The numerical model based on finite volume method is developed, and the non-equilibrium equation is applied to study the melting process of the paraffin embedded in aluminum foam. The heat loss, the liquid average velocity and the efficiency of latent heat storage are analyzed and discussed. The results show that adopting the aluminum foam with high PPI value or modifying the shape of the cold wall could improve the thermal response of composite. Besides, the discrete heat sources could lead to a large average velocity in the liquid region. Combining the advantages of these methods, an optimization method is also proposed, which could improve the efficiency to 83.32% comparing with the pure paraffin.

1. Introduction

Phase change material (PCM) can be applied in many domains, including solar energy storage, industrial waste heat recovery and electronic cooling due to its high latent heat and steady phase transition temperature [1–3]. Recently, the organic PCM draws the attention of many researchers, because its chemical stability and low density could benefit the energy storage system [4,5]. However, the organic PCM always suffers from the low thermal conductivity ($<0.2\ W\,m^{-1}\,K^{-1}$), which restricts its wide application. In order to improve the thermal response of PCM, various technologies are studied by using experimental and numerical methods, such as adding metal fins [6], dispersing the particles with high conductivity in PCM [7], changing the shape of container [8] and using the metal foam as skeleton [9].

Among these methods, embedding PCM in metal foam to make metal foam/PCM composite is considered so efficient that it becomes a popular area of research in the industry and science fields. In the study of the heat transfer in metal foam/PCM composite, it is found that the heat flux is transferred to the entire region along the ligaments of metal foam [10] and each PCM unit in the pore of metal foam could be heated by the metal foam matrix. Thus, the heat conduction of the composite is improved significantly by metal foam. Besides, the natural convection of the melting PCM also exists in the composite due to the porous structure of metal foam, which could enhance the heat transfer and make the temperature in the liquid region more uniform [11,12]. In this case, the addition of metal foam could enhance the heat transfer rate of PCM [13].

The heat transfer efficiency of the metal foam/PCM composite could be affected by many factors, such as structure of metal foam, container form and input power. Recently, in order to further improve the thermal performance of the composite, many research works have been conducted to optimize the structure of metal

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Nomenclature

A	interfacial area density, m^{-1}
c	specific heat, $J\,kg^{-1}\,K^{-1}$
C	consecutive number
C_i	inertial coefficient
d	diameter, m
D	area of cold surface, m^2
d_f	cell ligament diameter, m
d_p	cell pore average diameter, m
E	efficiency of latent heat storage, W
g	gravity, $m\,s^{-2}$
Gr	Grashof number
h	heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
H	characteristic length, m
K	permeability
k	thermal conductivity, $W\,m^{-1}\,K^{-1}$
L	latent heat, $J\,kg^{-1}$
Nu	Nusselt number
P	pressure, Pa
PPI	pore number per inch
Pr	Prandtl number
q	heat flux density, $W\,m^{-2}$
Q	quantity of heat, J
Re	Reynold number
S	source term
t	time, s
T	temperature, K
T_o	initial temperature, K
T_u	upper melting temperature, K
u, v	velocity in x, y directions, $m\,s^{-1}$
V	surface average velocity, $m\,s^{-1}$
v'	kinematic viscosity, $m^2\,s^{-1}$
x,y,z	Cartesian coordinates

Greek symbols

α	constant number
β	volume fraction of the liquid
ρ	density, $kg\,m^{-3}$
ε	porosity
μ	dynamic viscosity, $kg\,m^{-1}\,s^{-1}$
γ	thermal expansion factor, K^{-1}

Subscripts

0	initial
Al	aluminum foam
amb	ambient
ave	time-average
c	cold wall
f	fluid
fe	effective value of fluid
p	paraffin
s	solid
se	effective value of solid
total	total melting
w	hot wall

foam. Lafdi et al. [14] found that the metal foam with lower porosity or smaller pore size could enhance heat conduction and the higher porosity foam could be beneficial for the natural convection. Sundarram and Li [15] established a 3D model of metal foam, and they concluded that the smaller pore could help dissipate the heat more rapidly from the heat source. Yang et al. [16] utilized the metal foam with gradient porosity to accelerate the phase change process. Besides, some other methods could also be applied in the metal foam/PCM composite to improve the heat transfer efficiency, such as changing the container shape, modifying the distribution of the heat sources and varying the heat direction [17–19]. However, although these methods could all optimize the heat transfer of PCM, the comprehensive evaluation of their efficiencies is rare at present.

Therefore, the purpose of our work is to investigate the thermal performance enhancement methods of the composites (paraffin embedded in aluminum foam) and compare their efficiencies in the same condition. In this study, a two dimensions model is developed with finite volume method, and the non-equilibrium equation is used to study the melting process and natural convection in the container. The melting process, heat loss, average velocity of natural convection and the total melting time are analyzed and discussed. An optimization method realized by combining the advantages of these methods is also presented.

2. Description of methods and conditions

The metal foam used in this study is made by aluminum alloy AS7G, and paraffin wax is chosen as PCM, whose thermal properties are available in Ref. [20]. The physical model is the quadrilateral aluminum foam/paraffin composite with heat source and cold wall. Among the parameters of the physical model, the aluminum foam, cold wall and heat source are critical factors because they could affect the melting process of the paraffin embedded in aluminum foam. In order to improve the melting rate of paraffin, three enhancement methods are proposed based on these factors. Meanwhile, the different conditions in each method will be studied to obtain the most suitable structure and parameter. The schematic representation of the enhancement methods are illustrated in Fig. 1. Method I is changing the value of pores per inch (PPI). Cond.1, 2 and 3 represent the metal foam with 5, 10 and 20 PPI. Method II consists to changing the shape of the cold wall. In order to adapting the evolution of the liquid–solid interface, the cold walls of Cond.4 and 5 are sloped with respect to the horizontal surface, as shown in Fig. 1(b). Based on the form of liquid–solid interface, the cold wall with curved surface in Cond.6 is designed to optimize the heat transfer process. Method III is using the discrete heat sources. The total length of heat sources is 60 mm, and the number of the heat source is 2, 3 and 4 for Cond.7, 8 and 9, as shown in Fig. 1(c). The heat sources of each condition have the same length and the gaps between them are the same. The first heat sources contacts to the bottom surface and the others are arranged in order. Moreover, all the conditions have the same porosity and volume. The top and bottom surfaces are thermal insulation, and the heat in the sample is released to the atmosphere from cold wall with the heat transfer coefficient $10\,W\,m^{-2}\,K^{-1}$. The heat flux density of Method I and II is constant $3800\,W\,m^{-2}$, but the value of Method III is $5700\,W\,m^{-2}$, which is calculated based on the ratio of power to area.

3. Modeling method

3.1. Assumption

In order to simplify the simulation, several assumptions should be adopted: (1) The liquid is considered as incompressible and the flow in the liquid region is laminar; (2) The natural convection caused by buoyancy is subject to the Boussinesq approximation;