International Journal of Heat and Mass Transfer 84 (2015) 1008–1018

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

# Numerical analysis on thermal behavior of solid–liquid phase change within copper foam with varying porosity

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ARTICLE INFO

*Article history:*
Received 19 October 2014
Received in revised form 17 January 2015
Accepted 17 January 2015

*Keywords:*
Phase change in porous media
Linearly changed porosity
Thermal energy storage
Enhanced heat transfer

ABSTRACT

Structure of porous metal foam with linearly changed porosity was proposed to enhance phase change during thermal energy storage. Taking the melting process of sodium nitrate inside porous copper foam as example, a transient mathematical model was established to examine the influences of varying porosity on the thermal characteristic. Considering natural convection and Brinkman–Forchheimer extension to the Darcy law, the mathematical models were solved numerically and validated against experimental data from literature. The temperature variations and evolution of solid–liquid interface were explored and recorded. Two parameters, including liquid fraction of phase change material (PCM) and energy storage density, were defined to characterize the system performances. The influences of varying porosity in different average porosity and pore density were analysed. The results showed that porosity linearly increased from bottom to top could improve the heat transfer performance and shorten the completely melted time compared to that for constant porosity by enhancing natural convection. Nearly no negative effect on solidification was found by varying porosity because heat conduction dominated the solidified process.



## 1. Introduction

Solid–liquid phase change in porous media is a common procedure that occurs in many practical applications, such as latent heat thermal energy storage (LHTES), freezing of moist soils and manufacture of metal-matrix composites. In the system of LHTES, metal foam is used as thermal conductivity enhancers and phase change material (PCM) is impregnated into the foam severing to absorb or release energy during the proper time. Obviously, it is significant to understand the flow and heat transfer characteristics in porous media and the effect of geometry structure, such as porosity and pore density, on phase change process, which can lead to better design of the LHTES system.

Recently, there are numerous studies on melting or solidification in metal foam or other high porosity porous media [1–5]. The studies involving open-cell foams can be broken into four groups: the steady state calculation of effective thermal conductivity [6–15], the improvement of numerical method [16–22], the preparation of composite based on porous media and PCM [12,23–27] and the thermal performance analysis of heat transfer enhancement for high conductivity porous media [5,28–33].

Effective thermal conductivity is an important parameter to model and analyze this problem accurately. Boomsma et al. [10] and Bhttacharya et al. [13] developed their geometrical effective thermal conductivity model of saturated porous metal foam respectively based on the three-dimensional tetrakaidecahedron cell and two-dimensional hexagon cell. In their results, the corresponding calculated correlations are present to analyze the effective thermal conductivity. In Sedeh and Khodadadi's research [15], the structure of graphite foam saturated with PCM was modeled as a three-dimensional body-centered cube arrangement of uniform spherical pores. They obtained the empirical formulation and validated by their experiment. Paek et al. [9] carried out an experiment to determine the effective thermal conductivity. The results indicated that the effective thermal conductivity increased as the porosity decreased and the effect from cell size of the foam was not noticeable. Zhu et al. [34] put forward a novel method to calculate thermal conductivity of closed-cell aluminum foam based on the 3D reconstruction. The metal foam model was reconstructed by using MATLAB image processing and CT scanning.

Solid–liquid phase change process in porous media has been studied extensively over the years as it has many practical applications. So the numerical method is gradually improved. Nield and Bajan [18] reported a scaling analysis of PCM melting in porous matrix with local thermal equilibrium method. They found that the melting phenomenon in porous media was shown to pass

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.01.088
0017-9310/

**Nomenclature**

| | |
|---|---|
| $a$, $b$ | constant numbers to control porosity changed trend and range |
| $A$ | correlation constant for thermal conductivity |
| $A_{mush}$ | mushy zone constant |
| $c_p$ | specific heat, J/(kg K) |
| $c_F$ | inertial coefficient |
| $C_D$ | form drag coefficient |
| $d$ | characteristic length, m |
| $d_p$ | pore size, m |
| Da | Dacy number |
| $e$ | relative error |
| $E_t$ | specific enthalpy of composite at time $t$, J/kg |
| $f$ | liquid phase fraction for melting or solidification process |
| $f_l$ | liquid fraction in the pore for the volume element |
| $g$ | gravitational acceleration, m/s$^2$ |
| $G$ | shape factor |
| $h_p$ | specific enthalpy, J/kg |
| $H_L$ | latent heat of PCM, J/kg |
| $k$ | thermal conductivity, W/(m K) |
| $k_{eff}$ | effective thermal conductivity of composite, W/(m K) |
| $K$ | permeability, m$^{-2}$ |
| $L$ | standard value of relative error |
| PPI | pore number per inch |
| $Q$ | energy storage density, J/kg |
| $S$ | additional source term of momentum equations |
| $t$ | time, s |
| $T$ | temperature, K |
| $u$, $v$ | velocity in $x$, $y$ directions, m/s |
| $\vec{U}$ | velocity vector, m/s |
| $V_{molten}$ | molten volume of PCM, m$^3$ |
| $V_{PCM}$ | total volume of PCM, m$^3$ |
| $x$, $y$ | cartesian coordinates |

*Greek symbols*

| | |
|---|---|
| $\beta$ | thermal expansion coefficient of PCM, K$^{-1}$ |
| $\Delta$ | difference between measurement and stand value |
| $\varepsilon$ | porosity |
| $\bar{\boldsymbol{\varepsilon}}$ | average porosity |
| $\mu$ | dynamic viscosity of liquid phase PCM, (N s)/m$^2$ |
| $\rho$ | density, kg/m$^3$ |
| $\varphi$ | liquid fraction for the entire foam composite |
| $\chi$ | tortuosity coefficient |
| $\omega$ | pore density |

*Subscripts*

| | |
|---|---|
| $C$ | cooling |
| $f$ | PCM |
| $H$ | heating |
| $m1$ | the upper limit of melting state |
| $m2$ | the lower limit of melting state |
| $s$ | metal foam |

through four district regimes and each regime could be characterized by distinct Nusselt number. Tian [35] and Krishnan [19] considered the difference in thermal diffusivities between the metal foam and PCM. The two-temperature model was used to analyze both conduction and convection phenomena in porous media and the method were validated by their experiment. Lattice Boltzmann method was also used to simulate this problem. Gao et al. [20,36] developed a thermal lattice Boltzmann model for the melting with natural convection in porous media at the representative elementary volume scale. The local thermal equilibrium and non-equilibrium problems were considered in their numerical models.

The preparation of shape-stabilized PCMs/porous metallic matrix composite or PCMs/graphite foams composite is directly relevant to the widespread use of them. Sedeh et al. [27] proposed a numerical approach to simulate time-dependent evolution of the liquid front during the pore-level infiltration of liquids into porous structures. The various driving forces including pressure gradient, gravity and interfacial effects were all considered to analyze the interface behavior in penetration process. Xiao et al. [23] prepared paraffin/nickel foam and paraffin/copper foam composite PCMs using a vacuum impregnation method. The impregnation ratios were in the range of 92–98%. Py et al. [8] proposed a composite made of paraffin impregnated by capillary forces in compressed expanded natural graphite (CENG) matrix. The composite PCM/CENG thermal conductivity found to be in range of 4 to 70 W m$^{-1}$ K$^{-1}$ depending upon the bulk graphite density.

The Metal foam or other foams with high conductivity used to enhance the heat transfer of thermal energy storage system was mainly carried out by numerical and experimental method. Yang et al. [31] analyzed the thermal behaviors of high temperature latent heat thermal energy storage system, which was enhanced by both metal foam and fins, were investigated numerically. Solid–liquid interface was documented and the effect of geometry structure of metal foam and fins on melting process was discussed. Li et al. [32] used open-cell metallic foam to enhance conductivity of paraffin. The results showed that the liquid/solid movement rate was higher for the low porosity foam and the influence of pore density was less sensitive. Zhao [37] used copper and copper-steel alloy foam to enhance the heat transfer of PCM. The results showed that the charging and discharging period are reduced significantly. The conduction was greatly enhanced by metal foam in spite of the suppressed effect to the natural convection effect. Chen et al. [22] studied the melting behavior of phase change material in metal foam at the pore scale experimentally. The visual results showed that the conduction dominated the heat transfer mechanism in pore scale and natural convection exerted little influence on melting.

However, literature review regarding metal foam to enhance solid–liquid phase change found that nearly all the researches were carried out based on the given geometry structure including porosity and pore density. There are little studies to find out how to configure the porosity or pore density of metal foam to optimize the heat transfer process for thermal energy storage system. In the present study, a copper foam configuration with varying porosity is proposed, in which, melting behavior of PCM is investigated numerically. The present physical model attempts to verify the approach that can enhance the heat transfer during thermal energy storage by the optimization of porous media structure.

## 2. Physico-mathematical model

The physical model under investigation is shown in Fig. 1. A rectangular domain with length of $y = 30$ cm and width of $x = 10$ cm encloses the porous copper foam. The foam is filled with solid phase change material. Bauer et al. [38,39] used sodium nitrate as PCM for latent heat energy storage and thermal stability, compatibility and thermophysical properties were tested accurately. The results showed that sodium nitrate had excellent characterization in temperature range from 300 °C to 350 °C. So the sodium nitrate is chosen as PCM in this paper. The related thermal physical properties of PCM (at temperature 306 °C) and copper foam can refer to Table 1.