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Comparison of direct numerical simulation with volume-averaged method on composite phase change materials for thermal energy storage

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HIGHLIGHTS

- Volume-averaged method is compared with direct numerical simulation in phase change.
- DNS results reports significant temperature difference between ligaments and PCM.
- Natural convection strongly affects the melting front shape and temperature distribution.
- VAM with two-temperature model predicts well, although pore-scale features are lost.

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ABSTRACT

Melting heat transfer in open-cell metal foams embedded in phase-change materials (PCMS) predicted by the volume-averaged method (VAM) was systematically compared with that calculated using direct numerical simulation (DNS), with particular attention placed upon the contribution of natural convection in the melt region to overall phase change heat transfer. The two-temperature model based on the assumption of local thermal non-equilibrium was employed to account for the large difference of thermal conductivity between metallic ligaments and PCM (paraffin). The Forchheimer extended Darcy model was employed to describe the additional flow resistance induced by metal foam. For the DNS, a geometric model of metal foam based on tetrakaidehedron cells was reconstructed. The DNS results demonstrated significant temperature difference between ligament surface and PCM, thus confirming the feasibility of local thermal non-equilibrium employed in VAM simulations. Relative to the DNS results, the VAM combined with the two-temperature model could satisfactorily predict transient solid-liquid interface evolution and local temperature distribution, although pore-scale features of phase change were lost. The presence of natural convection affected significantly the melting front shape, temperature distribution and full melting. The contribution of natural convection to overall phase change heat transfer should be qualitatively and quantitatively given sufficient consideration from both macroscopic (VAM) and microscopic (DNS) point of views. Besides, practical significance and economic prospective using metal foam in TES unit for WHR system to provide residential heating or hot water is discussed and analyzed.

1. Introduction

The energy demand has increased sharply in the world in recent decades according to a summary of energy consumption for 69 countries, especially in developing countries that are accelerating urbanization process [1]. It is indicated that the demand for oil will increase by 30% while coal and natural gas will increase by 50% from 2007 to 2035. China is the biggest country for energy consumption worldwide with an increase rate of 18% in 2011, while the US, EU, India, Russia and Brazil follow behind. Research demonstrates that the energy consumption in China will increase to be more than 15 times by 2050 compared with that in 1970 [2]. The rapid consumption of

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Nomenclature

Abbreviation

DNS	Direct numerical simulation
Expt	Experimental measurement
MF	Metal foam
NS	Numerical simulation
TES	Thermal energy storage
PCM	Phase change material
PF	Plate fin
PPI	Pore per inch
VAM	Volume-averaged method
WHR	Waste heat recovery

Symbols

A_m	Numerical coefficient for damping velocity
C_E	Inertia coefficient (m^{-1})
C_p	Specific heat ($J\,kg^{-1}\,K^{-1}$)
C_h	Price for residential heat ($\$\cdot GJ^{-1}$)
C_{ut}	Specific material cost for metal foam ($\$\cdot m^{-3}$)
d_p	Pore diameter (m)
e	Thickness ratio of node to solid ligament
f_l	Melting fraction
Fo	Fourier number
G	Shape function for metallic ligaments
h_{sf}	Interstitial heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
k	Thermal conductivity ($W\,m^{-1}\,K^{-1}$)
L	Latent heat of fusion of PCM ($J\,kg^{-1}$)
N	Number of operating hours (h)
Nu	Nusselt number
$\overline{Nu}$	Integral mean Nusselt number
P	Pressure (Pa)
Q_c	Total stored energy (J)
T	Temperature (K)
t	Time (s)
u	Component velocity in x axis ($m\,s^{-1}$)
$\vec{U}$	Velocity vector ($m\,s^{-1}$)
v	Component velocity in y axis ($m\,s^{-1}$)
V	Void volume for a TES unit (m^3)
V_c	Fully charged volume for a TES unit (m^3)
w	Component velocity in z axis ($m\,s^{-1}$)
$\langle\rangle$	Extrinsic average of a quantity over a control volume
$\|\|$	Magnitude of a vector

Greek symbols

α	Cross-sectional area ratio of node to solid ligament
α_{sf}	Specific area (m^{-1})
β	Thermal expansion coefficient (K^{-1})
δ	Numerical constant
ε	Porosity
η	Percentage of welding to materials cost
ρ	Density ($kg\,m^{-3}$)
μ	Dynamic viscosity ($N\,s\,m^{-2}$)
Π	Yearly earned profit ($\$\cdot yr^{-1}$)
σ	Liquid fraction in the porous medium
χ	Flow tortuosity

Subscript

e	Effective parameter
f	Phase change material
full	Full melting rate
i	Initial state
m	Melting point
s	Solid ligaments
td	Thermal dispersion
w	Wall
1	Solid state
2	Liquid state

conventional fossil fuels has therefore caused a lot of serious energy and environmental issues, such as energy shortages, global warming, environmental pollution and etc. [3–5]. For the time being, convectional fossil fuels have still played the vital role in global energy supply. To mitigate the environment stress, on one hand, efforts have been paid to transferring the fossil fuel energy sources towards renewable energy, such as solar, wind, tidal and biomass and so on; on the other hand, turning “waste heat” to “useful heat” can also improve the overall energy efficiency of the existed energy systems, since about 20–50% of energy used in industry is rejected as waste heat [6,7].

Waste heat recovery (WHR) system is capable of collecting industrial “waste heat” and converting it to “useful heat” for incoming reactants preheating, electricity generation, hot water and central heating for residences, and so on. Thermal energy storage (TES) via absorbing/releasing latent heat by phase change materials (PCMs) is one of the proved approaches for WHR. However, the charging/discharging rate suffers significantly from the low thermal conductivity of engineering-utilized PCMs (e.g. paraffin ~ $0.2\,W\,m^{-1}\,K^{-1}$) [8], thus limiting its practical applications. To this end, various techniques have been developed to enhance phase change process. To be summarized, there are two main approaches according to the thermal enhancement spreader adopted: movable – micro/nano particles, or non-movable – porous matrix. Compared with the attainable enhancement by directly adding micro/nano particles into the PCMs [9], the impregnation of PCMs into highly porous metal foams with open cells is particularly promising for structural controllability and satisfactory thermal enhancement [10–13]. A series of studies have indicated that metal foams possess a superior performance in enhancing the thermal conductivity of PCMs during phase change process. To model the phase change process in a PCM-foam composite, two approaches are commonly employed according to the scale considered in the simulations: the volume-averaged method (VAM) and the direct numerical simulation (DNS).

The VAM typically treats the PCM-foam composite as an equivalent fluid with identical thermophysical properties, with pore-scale thermal fluid and geometric features lumped into the equivalent fluid. The predicted results demonstrate global fluid flow and heat transfer characteristics. Assuming local thermal equilibrium or non-equilibrium, one may employ the one- or two-temperature model. Pioneering work on thermal equilibrium assumption (one-temperature model) can be traced back to Beckermann and Viskanta [14], who applied volume-averaged transport equations to model the process of phase change in porous media. The topology of solid-liquid interface was found to be greatly influenced by the onset of natural convection in the melt phase. Feng et al. [15] and Yang et al. [16] applied the one-temperature model to simulate the phase change behavior of PCM saturated in open-cell metal foam, and found that the model may be suitable for solidification process.

As for melting heat transfer in porous media, the two-temperature model that considers the temperature difference between solid ligament surface and PCM may be more appropriate [17]. Assuming local thermal non-equilibrium, Mesalhy et al. [18] considered the Darcy-