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A novel experimental-numerical method for studying the thermal behaviors of phase change material in a porous cavity

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ABSTRACT

Experiment and numerical simulation were carried out in this work to investigate the thermal transport behaviors of Newtonian fluids, phase change material (PCM), and composite PCM in a cavity, filled with porous media for thermal energy storage (TES) applications. Herein a novel experimental system was developed by using numerous long and parallel steel wires embedded in the cavity to construct a two-dimensional (2-D) porous structure, which provided an accessible way for numerical simulation by directly meshing the porous structure. As Rayleigh number (*Ra*) over than 1.0E8, the flow was simulated by standard k-ε turbulent model. The effects of heat conduction through metal structure, natural convection of liquid PCM, and geometric configuration of porous medium and porosity on improving the thermal transport efficiency were discussed. For Newtonian fluid flow and heat transfer, higher Rayleigh number led to stronger natural convection, and the deviation between experimental and numerical is less than 10% that confirmed the reliability of numerical method for further application in phase change process; for phase change behavior of PCM in the cavity with wires, natural convection was apparently weakened as porosity (ε) decreased to 80% and heat conduction started to dominate the heat transfer. The full charging time ($t_{full,\ wire}$) of PCM mixed with wires was then compared to that ($t_{full,\ EG}$) of PCM mixed with expanded graphite (EG) under the same porosity. The results showed that EG significantly improved the heat transfer efficiency that $t_{full,EG}$ for four cases (ε = 95%, 90%, 85%, 80%) is only 24.4%, 9.5%, 5.7% and 4.0% of $t_{full,wire}$, respectively. This result indicates that when mixing PCM with material of high thermal conductivity to improve the thermal conductivity of composite PCM, the porosity and geometric configuration of the material are essentially needed to be considered. Furthermore, the cross-linked structure of material plays a more important role than porosity in enhancing thermal transport efficiency through heat conduction. This work brings deep insights into sensibly improving the thermal conductivity of PCM by adding materials with high thermal conductivity.

1. Introduction

In solar thermal power plants, thermal energy storage (TES) unit is a key component for improving its dispatchability. Recent developments and design recommendations for heat storage have been well addressed (Kuravi et al., 2013; Tian and Zhao, 2013). A TES unit is mainly composed of three parts, which are the thermal storage medium, heat transfer mechanism and containment system. Phase change materials (PCMs) have become popular as thermal energy storage media for the superiority in providing a large heat storage density and significant reduction of storage material volume by using their latent heat and isothermal behavior (Cárdenas and León, 2013; Ibrahim et al., 2017). Most of the available PCMs, including inorganic salts and organic materials, however have very low thermal conductivity ranging from 0.1 to 1.0 W/(m·K), which leads to great reduction in heat storage and extraction rates, and eventually lowers the overall power of the phase change regenerator (Agyenim et al., 2010). This limitation can be overcome by mixing PCM with materials of high heat conductivity, such as porous media, carbon fibers, exfoliated graphite and expanded graphite (EG) to enhance heat transfer rate (Zhao and Wu, 2011; Wang et al., 2013; Li et al., 2014; Gasia et al., 2016). The thermal conductivity of composite PCM/EG, for example, not only relies on the amount of graphite but the particle size and geometric configurations (Py et al., 2001; Pincemin et al., 2008; Li and Wu, 2017). As a kind of latent heat storage PCM, paraffin wax mixed with different porous media was studied by many researchers since it possesses desirable properties such as high latent heat, chemically inert, no phase segregation, and commercially available (Zhong et al., 2010; Luo et al., 2015; Tian et al.,

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Nomenclature

c_p	specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)
d	diameter (m)
g	gravity ($m \cdot s^{-2}$)
H	height (cm)
k	turbulent kinetic energy (J)
K	permeability (m^2)
l	characteristic length (m)
L	latent heat ($kJ \cdot kg^{-1}$)
n	number
p	pressure (Pa)
q	heat flux ($W \cdot m^{-2}$)
S	surface area (m^2)
t	time (s)
u, v, w	velocity in x, y, z coordinate, ($m \cdot s^{-1}$)
W	width (m)
T	temperature (K)
x, y, z	orthogonal coordinates (m)

Dimensionless number

Da	Darcy number
Gr	Grashof number
Ra	Rayleigh number

Latin

β	volumetric thermal expansion coefficient (K^{-1})
ε	porosity; turbulence model
φ	liquid fraction
λ	thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
η	dynamic viscosity (Pa·s)
ν	kinetic viscosity ($m^2 \cdot s^{-1}$)
ρ	density ($kg \cdot m^{-3}$)

Subscript

c	cold
f	fluid
h	hot
init	initial
m	melting
ref	reference
w	wall

2016). Paraffin wax thus was used as PCM in this work.

To study the fluid flow and heat transfer behaviors in porous media, experimental methods are limited to provide full field information, such as the flow structure and temperature map. Our former work (Wu and Zhao, 2011) conducted heat transfer experiments with $NaNO_3$ embedded in metal foam. They found high density of porous structures in TES could suppress natural convection, and heat transfer rate in liquid region of PCM was thus reduced by half. However, it lacked information on flow field and temperature map inside pores for further understanding.

Numerical methods, by contrast, have shown superiority in analyzing complicated fluid flow and heat transfer phenomena over last decades. Nevertheless, the complex characteristics of composites such as porous structure, irregular dispersion and discontinuous particles, pose challenges to numerical methods in predicting the thermal behaviors of a porous cavity with porous media in wide-spread weight fraction. Some empirical models or simplified assumptions have been adopted to study the heat transfer behaviors in porous media with connective structure (Krishnan et al., 2005; Siahpush et al., 2008; Liu et al., 2013; Li and Wu, 2014). A multi-scale model was developed in our latest work (Li et al., 2014) for predicting the effective thermal conductivity of composite PCM/EG. The deviations between the predicted results and experimental data are lower than 10%.

Natural convection in a square 2-D cavity of Rayleigh number (Ra) up to 1E8 was theoretically analyzed by Le Quere (1991), with accurate solution given to the governing equations. Braga and Lemos (2004) presented detailed numerical computations for laminar and turbulent natural convection within a square cavity in 2-D filled with a fluid saturated porous medium. The macroscopic k-ε turbulence model with wall function was used to handle turbulent flow in porous media. Darcy-Rayleigh number (Ra_m) equal to 1E4 was taken as a critical value for characterizing the laminarization phenomenon. Furthermore, when fluid and medium properties (porosity, Prandtl number, conductivity ratio between the fluid and the solid matrix) and the Ra_m were fixed, the lower Darcy number, the higher average Nusselt number on the hot wall. Oh et al. (1997) numerically studied the flow and heat transfer characteristics of natural convection at steady state in a vertical square enclosure, where a temperature difference exists across an enclosure and meanwhile a conducting body generates heat within the enclosure. The results showed that, as the temperature difference ratio increased, the transient flow due to natural convection dominated by the temperature difference across the enclosure proceeded to that dominated by the temperature difference between enclosure wall and the heat source. Raji et al. (2012) numerically investigated the effect of the subdivision of a solid block with variable thermal conductivity on the fluid flow and heat transfer characteristics inside a square cavity. The results showed that the subdivision of the block delayed the onset of natural convection and reduced the heat transfer. At high Ra, the subdivision of the solid blocks did not lead to any practical influence on the heat transfer. A direct numerical method was used by Pourshaghaghy et al. (2007) to simulate natural convection in a square porous enclosure, where the porous structure was formed by random distributed solid blocks. Navier-Stokes (N-S) equations for natural convection were solved directly. The results showed that the average Nusselt number in heat conduction dominant state was equaling to one, and the critical Rayleigh number was found in the range of 1E6–2E6.

Numerical simulation based on directly meshing a 2-D porous TES unit was carried out in our latest work (Li and Wu, 2017) to investigate the effects of porosity, the geometric configurations of dispersed particles, and Rayleigh number on the thermal transport efficiency of a cavity with Newtonian fluid in laminar state. The results showed that the Rayleigh number (Ra_K) considering the permeability of material could evaluate the roles of heat conduction and natural convection. When Ra_K is lower than 20.6, the heat conduction starts to dominate the heat transfer inside the composite that leads to the total heat performance of the composite with square particles is lower than that of the system with pure liquid PCM.

In this work, a novel experimental system was established to mimic fluid flow and thermal transport in a 2-D cavity with randomly distributed porous media. The simplified porous cavity provides an easy way for numerical simulation based on directly meshing porous structure. Not only single phase flow of Newtonian fluids with varied viscosity but also phase change processes of pure PCM-paraffin and composite PCM in TES with diverse porosity were tested to prove the reliability and feasibility of both experimental scheme and numerical method. Furthermore, the effects of porosity (ε) and geometric configuration of porous media on heat transfer efficiency of TES unit were analyzed, and the roles of heat conduction and natural convection were discussed