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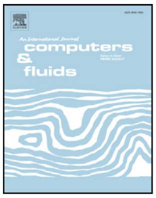

Direct numerical method for studying heat transfer behaviors in an enclosure with dispersed thermal conductive particles

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ABSTRACT

Numerical simulations in a two-dimensional (2-D) thermal energy storage (TES) unit were carried out to investigate the thermal behaviors of phase change materials (PCMs) - sodium nitrate ($NaNO_3$) inside porous media. The porous media are composed of randomly distributed particles with high thermal conductivity. The effects of heat conduction through particles, natural convection of liquid PCM, and the geometric parameters such as porosity and particle shape were numerically examined. The results show that for the TES dispersed with square particles, the heat transfer coefficient of the system can be increased up to 27–310% for the porosity ranging from 60% to 90%; while for the particles of expanded graphite (EG)-like structure, the heat transfer coefficient of the TES at 60% porosity can be raised as much as 93.3 times. The high weight fraction of particles in the TES could depress the happening of natural convection, especially for EG-like particles. The Rayleigh number considering the permeability of material (Ra_K) was proposed to 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.

1. Introduction

The solid-liquid thermal storage systems based on the latent heat of PCMs are already well-known by taking advantages of their high energy storage density and isothermal behavior [19,23]. Most of available PCMs however have very low thermal conductivities 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 [1,11]. This disadvantage hence limits PCMs applications in TES. Mixing the materials with high heat conductivity into PCMs, such as porous media, carbon fibers and exfoliated graphite, has been attempted in last years to overcome such limitations to enhance heat transfer rate [2,3,5].

Expanded graphite (EG) is an attractive porous medium combined with PCMs to prepare composites, for its high thermal conductivity (~200 W/(m K)), chemical stability and low cost. EG is obtained from expandable graphite powder [8] to create porous matrix with large specific surface area and struts connected. Researchers have made efforts in developing high heat performance of TES based on EG/PCMs composites [7,14,24,26]. The thermal conductivity of PCM composite not only relies on the amount of graphite but the particle size [14,16]. High density of porous structure in TES however was found to suppress natural convection [25], the heat transfer rate in liquid region of PCM was thus reduced by half.

For fluid flow and heat transfer mechanism in porous media, experimental methods are limited to provide detailed information such as the flow structure and temperature gradient field. Numerical methods 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 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 [9,10,20]. A multi-scale model was developed in our latest work [8] for predicting the effective thermal conductivity of PCM/EG composite. The deviations between the predicted results and experimental data are lower than 10%. However, still few open references have ever carried out direct numerical simulation to comprehensively study how heat conduction and natural convection influence the thermal transport mechanism in a TES unit, with randomly dispersed particles to form non-connective porous structure.

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Nomenclature

A	[m^2] (Area)
g	[m/s^2] (Gravity)
l	[m] (Characteristic length)
K	[m^2] (Permeability)
n	Normal direction
p	[Pa] (Pressure)
T	[K] (Temperature)
u, v	[m/s] (Velocity in x, y direction, respectively)
x, y	[m] (Cartesian axis direction)
P	Dimensionless pressure
U, V	Dimensionless velocity in X, Y direction, respectively
X, Y	Dimensionless axis of x, y, respectively
Da	Darcy number
Gr	Grashof number
Nu	Nusselt number
Pr	Prantdl number
Ra	Rayleith number
Re	Reynolds number
Special characters	
α	[m^2/s] (Thermal diffusivity)
λ	[W/m·K] (Thermal conductivity)
Θ	Dimensionless temperature
ε	Porosity
ν	[m^2/s] (Kinetic viscosity)
Subscripts	
c	Cold surface
f	Fluid phase of PCM
h	Hot surface
i	Grid number
s	Solid phase

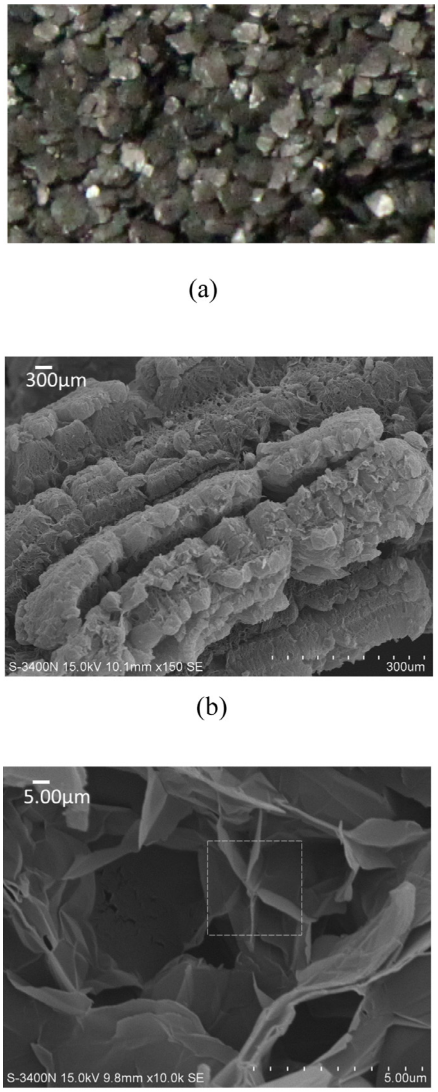
(a)
(b)
(c)

Fig. 1. (a) Expandable graphite powder, (b) expanded graphite (EG) powder magnified by 150× and (c) micro-structures of EG magnified by10,000×.

Natural convection in a square 2D cavity of Rayleigh number (Ra) up to 10^8 was theoretically analyzed by Le Quere [6], with accurate solutions given to the governing equations. Oh et al. [12] 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 show that as the temperature difference ratio increases, the flow dominated by the temperature difference across the enclosure proceeds to that dominated by the temperature difference due to the heat source. Raji et al [17] 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. Their results showed that the subdivision of the block delays the onset of natural convection and reduces the heat transfer. At high Ra, the subdivision of the solid blocks does not lead to any practical influence on the heat transfer. A direct numerical method was used by Pourshaghaghy et al. [15] 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 is equal to one, and the critical Rayleigh number was found in the range of 10^6 –2×10^6.

Our current work focuses on numerically analyzing the heat transfer characteristics of a two-dimensional (2-D) TES unit, randomly dispersed with high conductive composites of PCM/expandable graphite and PCM/EG**.** We choose inorganic material - sodium nitrate ($NaNO_3$) as PCM. The commercial softwares of *Gambit* and *Fluent 13* are used to generate mesh and solve the governing equations, respectively. The physical models, numerical methods and simulation results for flow and heat transfer inside the TES with and without porous medium are presented in the following sections. Effects of geometric parameters including particle shape and porosity (ε) on the heat transfer efficiency of the TES unit are analyzed. Particularly, the roles of heat conduction and natural convection are discussed to further understand the liquid phase flow and thermal transport mechanism in such a TES unit.

2. Numerical methodology

2.1. Schematic of TES

Expandable graphite particles (Fig. 1(a)) are used to obtain porous expanded graphite (EG) particles in experiments, with structure connected by thin graphite flake in microscale (Fig. 1(b,c)). The complex configuration of composites makes it nearly impractical to directly mesh the dispersive particles into independent grids without simplified assumptions. To mimic the geometric configurations of expandable graphite and EG particles as marked by the dash line in Fig. 1(c), the square (Fig. 2(a,b)) and L-shape

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