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Lattice Boltzmann simulation of the double diffusive natural convection and oscillation characteristics in an enclosure filled with porous medium

H.T. Xu [a], T.T. Wang [a], Z.G. Qu [b,*], J. Chen [a], B.B. Li [a]

[a] School of Energy and Power Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China
[b] MOE Key Laboratory of Thermo-Fluid Science and Engineering, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China

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ABSTRACT

This article adopts lattice Boltzmann method to investigate the double diffusive natural convection around a heated cylinder in an enclosure filled with porous medium. The heated cylinder is located at the center of the enclosure with high temperature and concentration. Four surrounding walls are assumed to be low temperature and concentration. The distributions of velocity, temperature and concentration are solved by three independent lattice Bhatnagar-Gross-Krook (LBGK) equations. The influence of Darcy number Da ($10^{-4} \le Da \le 10^{-2}$), Lewis number Le ($0.2 \le Le \le 10.0$) and buoyancy ratio Br ($-10.0 \le Br \le 10.0$) on the double diffusive natural convection are inspected numerically. Results are presented in terms of isotherms, streamlines, isoconcentrations, average Nusselt and Sherwood numbers. At $Br = -50.0$, the effect of Darcy number on unsteady flow characteristics is also investigated by the time history and phase space trajectory. It is found that the flow undergoes steady-state, unsteady doubling periodic oscillation, quasi-periodic oscillation and non-periodic oscillation when Darcy number Da is varied from 10^{-4} to 10^{-2}.

1. Introduction

Porous media is widely adopted at material engineering, thermodynamic engineering, and micro-combustion etc. Zhao and Tang [1] used Monte Carlo method to determine the extinction coefficients of silicon carbide porous media made up of random sphere pores. Wu et al. [2] proposed a pore network model to account for the capillary valve effect induced by the sudden geometrical expansion of the void space during slow drying of porous media. Wu et al. [3] adopted Brinkman-Darcy-Forchheimer model and energy equation to simulate the natural convection inside the porous media between vertically eccentric annuli. Vignoles [4] presented a computational simulation tool for the heat transfer, combing solid-phase conduction and linearized radiative transfer in porous media with opaque solid phases. Tang et al. [5] experimentally studied the effect of structural parameters on pool boiling heat transfer for porous interconnected micro channel nets. Li et al. [6] added porous medium to a free flame micro-combustor to enhance thermal energy transport and numerically studied the flame characteristics of premixed H_2-air combustion. Rashidi et al. [7] performed a sensitivity analysis to calculate the effects of porous material on the heat transfer rate and pressure drop inside a porous solar heat exchanger.

Double diffusive convection in porous medium is a common phenomenon in the field of industrial engineering. Compared with the pore-scale simulation, the representative elementary volume (REV) scale study determines statistically the macroscopic quantities and is widely adopted in the heat and mass transfer study. Chamkha and Hameed [8] carried out a numerical study of unsteady laminar double-diffusive convective flow of a binary gas mixture in an inclined porous enclosure. Effects of the inverse Darcy number and the enclosure tilting or inclination angle on the contours of streamline, temperature, concentration and density were studied. Masuda et al. [9] investigated oscillatory double-diffusive convection in a porous enclosure due to opposing heat and mass fluxes on the vertical walls. Costa [10] investigated the double-diffusive natural convection problem in parallelogrammic enclosures filled with fluid-saturated porous media. The influences of inclination angle, length width ratio and the buoyancy ratio are discussed. Al-Farhany and Turan [11] investigated two dimensional double-diffusive natural convective heat and mass transfer in an inclined rectangular porous medium. The non-dimensional parameters included aspect ratio ($2 \le A \le 5$), angle of inclination of the cavity ($0 \le \varphi \le 85$), Lewis number ($0.1 \le Le \le 10$) and the buoyancy ratio ($-5 \le Br \le 5$). Jena et al. [12] analyzed buoyancy opposed double diffusive natural convection in a square porous cavity with partially active thermal and solutal walls. The effects of buoyancy ratio, Darcy number and active zone locations on the heat and mass transfer have been

* Corresponding author.
E-mail address: zgqu@mail.xjtu.edu.cn (Z.G. Qu).

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Nomenclature

Br	buoyancy ratio
C	mass concentration, kg/m^3
C_h	concentration around the cylinder, kg/m^3
C_c	concentration of side walls of enclosure, kg/m^3
c	the particle speed
c_s	sound velocity
C_i^{eq}	the equilibrium distribution function for concentration
D_e	the effective mass diffusivity, m^2/s
Da	Darcy number, $Da = K/L^2$
$\boldsymbol{F}$	the total force
f_i^{eq}	the equilibrium distribution function for velocity
$\boldsymbol{g}$	acceleration of gravity, m/s^2
G	the buoyancy force term
H	cavity height, m
J	viscosity ratio
$\mathbf{j}$	the unit vector in the y-directions
K	the permeability
L	cavity width, m
Le	Lewis number, $Le = \alpha/D$
Nu_{av}	the average Nusselt number
n	outward normal direction
p	pressure, N/m^2
P	dimensionless pressure, $P = p/\rho u_R^2$
Pr	Prandtl number, $Pr = \nu_e/\alpha_e$
Ra_T	thermal Rayleigh number, $Ra_T = g\beta_T(T_h - T_c)L^3/(\nu_e\alpha_e)$
S	dimensionless concentration
Sh_{av}	average Sherwood number
T	local temperature, K
T_h	temperature around the cylinder, K
T_c	temperature of side walls of enclosure, K
T_i^{eq}	the equilibrium distribution function for temperature
u	velocity component in x direction, m/s
u_R	reference velocity, m/s
U	dimensionless velocity component in X direction
v	velocity component in y direction, m/s
V	dimensionless velocity component in Y direction
x, y	dimensional coordinates, m
X, Y	dimensionless coordinates

Greek symbols

α_e	the effective thermal diffusivity, m^2/s
β_t	coefficient of thermal expansion, K^{-1}
β_c	coefficient of solutal expansion, m^3/kg
ν_e	the effective coefficient of kinematics viscosity, m^2/s
τ	non-dimensional time
τ_f	non-dimensional relaxation time for the velocity distribution function
τ_T	non-dimensional relaxation time for the temperature distribution function
τ_c	non-dimensional relaxation time for the concentration distribution function
θ	dimensionless temperature
$\varnothing$	the rotation radian of the heated cylinder, rad

studied. Elbouzidi [13] studied numerically the natural convection and thermosolutal in a rectangular cavity filled with porous medium using the Runge-Kutta method. The influences of Prandtl number, Darcy number and Rayleigh number on the flow behavior were investigated. Marcelo [14] used the two-energy equation model to analyze the turbulent double-diffusive free convection in porous media. Harfash and Hill [15] simulated a three dimensional double-diffusive throughflow in internally heated anisotropic porous media. The linear threshold could accurately predict the onset of instability in the steady state throughflow. Mondal and Sibanda [16] studied the buoyancy ratio effect on unsteady double-diffusive natural convection in a cavity filled with porous medium with non-uniform boundary conditions. Hadidi and Bennacer [17] presented the numerical results of three-dimensional double diffusive natural convection across a cubical enclosure partially filled by vertical porous layer. The influencing parameters included buoyancy ratio ($-4 \le Br \le -0.1$), Lewis number ($0.1 \le Le \le 10$) etc. Groşan et al. [18] presented the study of steady natural convection in a two-dimensional porous square cavity filled with a nanofluid and including internal heat generation. Dastmalchi et al. [19] investigated the effects of double-diffusive natural convection of Al_2O_3-water nanofluid on flow field and heat transfer in a porous square cavity. Kefayati [20] numerically studied the double diffusive natural convection and entropy generation of power-law fluids in an inclined porous cavity with Soret and Dufour effects.

Compared to conventional numerical methods, the lattice Boltzmann (LB) method is another powerful numerical tool to predict the flow and heat transfer characteristics. LB method is based on the mesoscopic kinetic equation (i.e., Boltzmann equation) to determine macroscopic fluid dynamics. This method reveals many advantages as the simplicity in calculation, adaptation to complex geometries, stability, accuracy and computing time saving. It has been widely adopted in the field of complex flows [21], multiphase [22] and nanofluid [23–27] etc. Guo and Zhao [28] investigated laminar convection of fluid with a temperature-dependent viscosity in an enclosure filled with porous medium by LB method. Haghshenas et al. [29] simulated natural convection in an open-ended square cavity packed with porous medium by LB method. A comprehensive parametric study of natural convective flows was performed for various values of Rayleigh number and porosity. Ridha et al. [30] developed a thermal LB model to investigate the natural convection flow in porous media under the effect of uniform magnetic field. The Rayleigh number, Hartmann number, Darcy number, medium inclination angle, magnetic field orientation and medium porosity effects were carried out in wide ranges. Li et al. [31] adopted LB model to

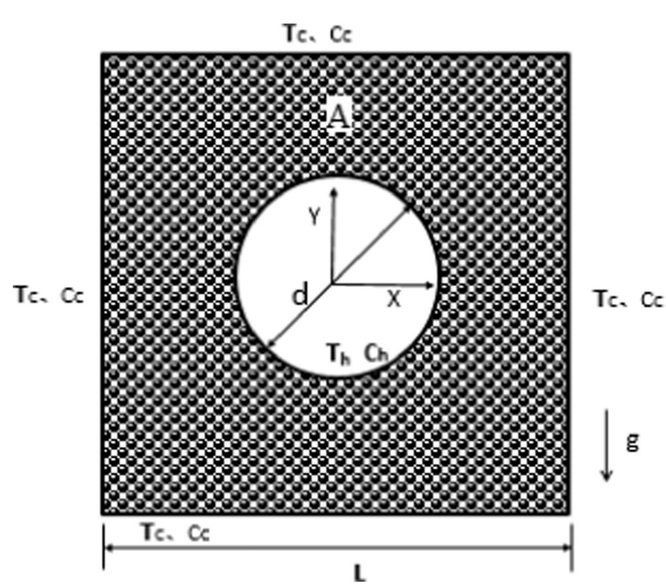

Fig. 1. Schematic diagram of the physical model.