International Journal of Heat and Mass Transfer 105 (2017) 673–683

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

A modified lattice Boltzmann model for conjugate heat transfer in porous media

Dongyan Gao [a,*], Zhenqian Chen [b], Linghai Chen [a], Dongliang Zhang [a]

[a] School of Energy and Power Engineering, Nanjing Institute of Technology, Nanjing, Jiangsu 211167, PR China
[b] School of Energy and Environment, Southeast University, Nanjing, Jiangsu 210096, PR China

ARTICLE INFO

Article history:
Received 3 September 2016
Received in revised form 7 October 2016
Accepted 7 October 2016

Keywords:
Lattice Boltzmann method
Conjugate heat transfer
Natural convection
Porous media

ABSTRACT

A modified lattice Boltzmann model for conjugate heat transfer in a system containing simultaneously a porous medium and other media is proposed. In this model, the volumetric heat capacity and a new parameter are introduced to the equilibrium temperature distribution function for satisfying the temperature and heat flux continuities at the interface between two phases with different thermal properties (thermal conductivity and volumetric heat capacity), as well as avoiding any correction of distribution functions neighboring the interface. The macroscopic temperature equations are correctly recovered from the corresponding lattice Boltzmann equations by the Chapman–Enskog procedure. Detailed numerical tests of the proposed model are carried out for several benchmark problems including steady-state conjugate heat conduction within two-layer solid medium, transient conjugate heat conduction in infinite composite solid, conjugate natural convection in a cavity partially filled with porous medium and conjugate heat transfer in porous media with a conducting wall. The present numerical results are in excellent agreement with analytical and numerical solutions reported in previous studies. Therefore, it is verified that the present model can be served as a feasible tool for conjugate heat transfer problems in porous media.

© 2016 Elsevier Ltd. All rights reserved.

1. Introduction

Conjugate heat transfer in a system containing simultaneously a porous medium and other media is frequently encountered in many scientific and engineering problems, such as the finned metal foam heat sink, the solidification in porous media, energy conservation in building, nuclear reactor and so on. Due to its fundamental and practical significance, this topic has received growing attention in the past several decades [1]. Some researchers have investigated different types of porous/solid conjugate heat transfer problems, such as natural convection in a porous cavity with horizontal or vertical conductive walls [2–5], natural convection in a vertical porous layer sandwiched by finite thickness walls [5–7] and conjugate heat transfer in porous medium with conductive fin or body [8–10]. On the other hand, other researchers have investigated porous/fluid conjugate heat transfer within cavities composed of both porous and fluid layers [11–13]. With few experimental tests, most of above studies are examined numerically due to the inherent geometrical complexity of porous medium. When numerical simulating these porous/fluid or porous/solid coupled heat transfer problems, one needs to consider continuities of temperature and normal heat flux at the interface between different phases, which are frequently called as conjugate conditions. However, such interface conditions cause much additional computational cost which is nearly unacceptably huge for traditional computational fluid dynamics (CFD) methods in complex geometries [14].

As an alternative numerical technique to the traditional CFD method, the lattice Boltzmann method (LBM) has received great attention in the simulation of fluid flow and heat transfer in porous media due to its simplicity and ability to handle complex geometry and boundary conditions [15–30]. As reported in Ref. [22], the LBM needs less computational time than the finite difference method to obtain the same accurate solutions of natural convection in porous media on the same grid size. To simulate fluid flow and heat transfer in porous medium using LBM, there are generally two methods adopted: the pore scale approach [16–20] and the representative element volume (REV) scale approach [21–30]. The former needs detailed geometric information of porous matrix, and thus the size of computation domain cannot be too large due to limited computer resources. In contrast to the former, the latter is simpler and more efficient, because average transport properties are only considered in this approach. In the past years, some Lattice Boltz-

---

* Corresponding author.
E-mail address: njgdy2010@163.com (D. Gao).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.10.023
0017-9310/© 2016 Elsevier Ltd. All rights reserved.

Nomenclature

b	number of discrete velocites
c	lattice speed, (m/s)
c_p	specific heat at constant pressure (kJ/(kg K))
c_s	sound speed (m/s)
Da	Darcy number, $Da = K/L^2$
d_p	pore diameter (m)
$\boldsymbol{e}_i$	discrete lattice velocity in direction i (m/s)
f_i	density distribution function in direction i (kg/m^3)
f_i^{eq}	equilibrium distribution function of density in direction i (kg/m^3)
$\boldsymbol{F}$	body force per unit mass (N/kg)
$\boldsymbol{F}_i$	discrete body force in direction i (kg/(m^3 s))
Fo	Fourier number, $Fo = \alpha t/L^2$
F_ε	Forchheimer form coefficient
$\mathbf{g}$	acceleration due to gravity (m/s^2)
g_i	temperature distribution function in direction i (K)
g_i^{eq}	equilibrium temperature distribution function in direction i (K)
H	height of the domain or characteristic length (m)
$\mathbf{I}$	unit tensor
J	viscosity ratio, $J = \nu_e/\nu_f$
k	thermal conductivity (W/(m K))
K	permeability (m^2)
L	weight of the domain or characteristic length (m)
n	dimensional number
Nu_{aver}	average Nusselt number
p	pressure (Pa)
Pr	Prandtl number, $Pr = \nu_f/\alpha_f$
$\boldsymbol{r}$	space positon (m)
Ra	Rayleigh number, $Ra = \lvert\mathbf{g}\rvert\beta\Delta TL^3/(\nu_f\alpha_f)$
Su_i	discrete source term related to velocity (W/m^3)
t	time (s)
T	temperature (K)
T_c	temperature of cold wall (K)
T_h	temperature of hot wall (K)
$\boldsymbol{u}$	velocity (m/s)
V	temporal velocity (m/s)
x, y, z	Cartesian coordinates (m)

Greek symbols

α	thermal diffusivity (m^2/s)
β	coefficient of thermal expansion (1/K)
γ	a constant parameter
δx	lattice space (m)
δt	time step (s)
ε	porosity of porous media
ν	kinematic viscosity (m^2/s)
ξ	small expansion parameter
ρ	density (kg/m^3)
σ	ratio of volumetric heat capacities of solid matrix and fluid
τ_f, τ_T	dimensionless relaxation time
ω_i	weight number in direction i

Subscripts

e	effective or equivalent
f	fluid
i	direction i in a lattice
s	solid matrix of porous medium
w	solid wall

mann models at the REV scale have been proposed for simulating the fluid flow and heat transfer in porous media [20–30].

An importance feature of the LBM is its ability to capture the fluid behavior near the interface of different phases. As one would expect, the LBM can also be applied to handle conjugate heat transfer problem in porous media. However, few lattice Boltzmann (LB) numerical studies have been conducted in the available literatures. In Ref. [21], the conjugate natural convection problems of a porous layer occupying partially in the middle of the square cavity have been investigated by the LBM proposed by Guo and Zhao [21]. Shokouhmand et al. performed LB simulations of convection heat transfer between two parallel plates of a conduit partially filled with a porous media [23]. Recently, Hu et al. have numerically examined natural convection in a square enclosure with a cylinder covered by a porous layer in the frame of LBM [30]. However, these existing studies were limited to steady-state porous/fluid conjugate heat transfer problems. In addition, to the best of our knowledge, these previous LB models for conjugate heat transfer are only effective for steady state problems and for the situation where heat capacity keeps unvaried between different phases. This is because that the conjugate conditions at the fluid/porous interface are satisfied automatically through the variation of the relaxation time during the collision step, which relates the spatial variation of thermal diffusivity in these previous models (the spatial variation of thermal conductivity and heat capacitance are coupled), and the continuity conditions of the temperature and heat flux in a transient analysis cannot be simultaneously satisfied when heat capacity varies [31,32]. As we all know, the heat capacitances between two phases are generally independent and not identical.

The objective of the present work is to extend the LBM to copy with conjugate heat transfer problems in porous media at the REV scale, as well as investigating its practicability and accuracy. For this purpose, the volumetric heat capacity and a new parameter are introduced into the equilibrium temperature distribution function and thus a modified LB formulation is proposed to handle the difference in both thermal conductivity and volumetric heat capacity at the porous/solid or porous/fluid interface for ensuring conjugate conditions. In addition, with a modified equilibrium temperature distribution and an additional discrete source term in the evolution equation modeling for the temperature field, a general form of energy equation can be correctly recovered through the Chapman–Enskog procedure. The remainder of the present paper is organized as follows. Section 2 presents a set of macroscopic equations for fluid flow and heat transfer in a system containing simultaneously a porous medium and other media. In Section 3, the double distribution function approach is employed to construct a thermal LB model for conjugate heat transfer in porous media. In this model, a modified LB formulation for the temperature field is presented and followed by the Chapman-Enskog analysis. In Section 4, detailed numerical tests are carried out to test the practicability and accuracy of the modified LB model. A brief conclusion is drawn in Section 5.

2. Generalized macroscopic governing equations

As shown in Fig. 1, the conjugate heat transfer problem in multi-domain or multiphase system is considered. The entire computational domain is composed by the porous region Ω_1 and other

Download English Version:

https://daneshyari.com/en/article/4994723

Download Persian Version:

https://daneshyari.com/article/4994723

Daneshyari.com