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A thermal lattice Boltzmann model for natural convection in porous media under local thermal non-equilibrium conditions

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ABSTRACT

A thermal lattice Boltzmann model for natural convection in porous media under local thermal non-equilibrium conditions is proposed through an appropriate selection of equilibrium distribution functions and discrete source terms. In this model, two new distribution functions are introduced to simulate the temperature fields of the fluid and solid matrix phases in addition to the density distribution function for the velocity field. The macroscopic energy equations are recovered from the corresponding lattice Boltzmann equations by the Chapman–Enskog procedure. Detailed numerical tests of the proposed model are carried out for three different cases under both steady state and transient conditions. The influence of various parameters such as ratio of solid-to-fluid thermal conductivities, interstitial Nusselt number, Rayleigh number, and Darcy number on the thermal and flow fields is investigated. The present numerical results agree well with the solutions reported in previous studies. Therefore, it is verified that the present model can be served as a feasible and efficient tool for non-equilibrium natural convection problems in porous media.

1. Introduction

Natural convection in porous media has long been the subject of both scientific and engineering investigations in view of its wide range of applications, such as in geothermal systems, underground spread of pollutants, thermal management of electronics, nuclear reactor and so on. It has been frequently investigated by invoking the assumption of local thermal equilibrium (LTE) between the working fluid and solid matrix [1,2]. In many practical applications, however, the assumption of LTE will break down [3]. For instance, when studying a rapid transport of heat in porous media [4], or when there is a significant internal heat generation occurring in fluid phase or solid phase [5,6], or when the difference in thermal conductivities and heat capacities between fluid and solid phases is significant, the local rate of change of temperature for two phases will be no longer equal and thus the assumption of LTE must be discarded [7–9], as pointed out by Minkowycz [4], Kaviany [3] and many others. In the local thermal non-equilibrium (LTNE) situations, instead of having a single energy equation which describes the heat transfer of the system, two energy equations are usually adopted to model the temperature fields of the fluid and solid phases [5–14]. In addition, appropriate coupling is necessary between the solid and fluid phase energy equations to account for the interfacial heat transfer.

The lattice Boltzmann method (LBM), developed over the last two decades, has emerged as a powerful approach for studying complex fluid flow, heat transfer and other complicated physics [15–18]. Compared with traditional computational fluid dynamics methods, it has many attractive advantages, such as its simple implementation, parallelizability and ability to handle complex geometry and boundary conditions such as those in porous media. When applying the LBM to model fluid flows and transport problems in porous media, these are generally two approaches, i.e. the pore scale approach and the representative element volume (REV) scale approach. The LBM at the pore scale is the most direct way to modeling fluid flows in particular and transport problems with complex pore geometry by the standard lattice Boltzmann (LB) equation and can obtain local information of the transport behaviors. Therefore, this method is effective to study the macroscopic relations and the microscopic mechanism of flow and transport processes through porous media. Early in 1989, the first LB application for flows in random porous media was performed by Succi et al. [19]. Later, the LBM at the pore scale has been extensively adopted for investigating transport problems in porous media [20–28]. However, it needs detailed geometric information of porous matrix, and thus the size of computation domain cannot be too large due to limited computer resources. An alternative approach is the LBM at the REV scale where average transport

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Nomenclature

b	number of discrete velocities
c	lattice speed, (m/s)
c_p	specific heat at constant pressure (kJ/(kg K))
c_s	sound speed (m/s)
Da	Darcy number, $Da = K/H^2$
d_p	pore diameter (m)
$\boldsymbol{e}_i$	discrete lattice velocity in direction i (m/s)
En	enthalpy (kJ/kg)
En_l	enthalpy at the end of melting (kJ/kg)
En_s	enthalpy at the beginning of melting (kJ/kg)
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, $Fo = \alpha t/H^2$
F_ε	Forchheimer form coefficient
$\boldsymbol{g}$	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)
Ha	dimensionless internal heat source, $Ha = qH^2/(\Delta T k_f)$
h_V	volumetric heat transfer coefficient (W/(m^3 K))
$\boldsymbol{I}$	unit tensor
J	viscosity ratio, $J = \nu_e/\nu_f$
k	thermal conductivity (W/(m K))
K	permeability (m^2)
La	latent heat of melting (kJ/kg)
n	dimensional number
Nu_p	interfacial Nusselt number based on pore diameter, $Nu_p = h_V d_p^2/k_f$
Nu_V	interfacial Nusselt number, $Nu_V = h_V H^2/k_f$
p	pressure (Pa)
P	dimensionless pressure, $P = pH^2/(\rho\nu\alpha)_f$
Pr	Prandtl number, $Pr = \nu_f/\alpha_f$
q	internal heat source term (W/m^3)
$\boldsymbol{r}$	space position (m)
Ra	Rayleigh number, $Ra = \lvert\boldsymbol{g}\rvert\beta\Delta T H^3/(\nu_f\alpha_f)$
Sr, Sr_i	source term, discrete source term (W/m^3)
Su_i	discrete source term related to velocity (W/m^3)
Ste	Stefan number, $Ste = c_{p,f}\Delta T/La$
t	time (s)
T	temperature (K)
T_c	temperature of cold wall (K)
$T_{f,l}$	temperature at the end of PCM melting (K)
$T_{f,s}$	temperature at the beginning of PCM melting (K)
T_h	temperature of hot wall (K)
T_m	melting temperature (K)
U	dimensionless velocity, $U = \boldsymbol{u}H/\alpha_f$
$\boldsymbol{u}$	velocity (m/s)
V	temporal velocity (m/s)
x, y, z	Cartesian coordinates (m)
X, Y, Z	dimensionless coordinates, $X = x/H$, $Y = y/H$, $Z = z/H$

Greek symbols

α	thermal diffusivity (m^2/s)
β	coefficient of thermal expansion (1/K)
Γ	ratio of thermal diffusivity of solid matrix and fluid
γ	liquid fraction in pore space
δx	lattice space (m)
δt	time step (s)
ε	porosity of porous media
θ	dimensionless temperature, $\theta = (T - T_{ref})/\Delta T$
λ	ratio of thermal conductivity of solid matrix and fluid
λ_e	ratio of equivalent thermal conductivity to fluid thermal conductivity
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

properties are only considered. This approach has been proved to be simple and computationally efficient method for modeling and solving transport problems in porous media [29–33].

The LBM at the REV scale is generally accomplished by including an additional term to the standard lattice Boltzmann equation (LBE) to account for the presence of a porous medium [29–35]. Guo and Zhao [31] developed a LB model to solve incompressible flow in porous media modeling the Navier–Stokes equation at the REV scale, in which the main idea is to include the porosity into the equilibrium distribution functions and add a forcing term accounting for the drag forces of the medium. Guo and Zhao [32] further extended LBM to modeling the natural convection in porous media, in which a density distribution function equation is used for modeling the velocity field, while another temperature distribution function equation for simulating the temperature field. Their numerical results agreed well with the numerical solutions in the literature. Seta [33] confirmed the reliability and computational efficiency of LBM in simulating these types of problem. Shokouhmand et al. [34] performed simulations of laminar flow and natural convection heat transfer between two parallel plates of a conduit filled with a porous media fully and partially by means of the LBM. Rong et al. [34] employed the LBM to simulate free convection flow through an annular filled with porous media. Gao and Chen [36] applied the LBM to model natural convection with phase change in porous media. However, almost all of previous LB models [29–36] for natural convection in porous media are based on the single energy equation and the assumption of local thermal equilibrium.

The aim of this work is to extend the LBM to copy with natural convection in porous media under local thermal non-equilibrium conditions, as well as investigating its practicability and accuracy. To this purpose, through an appropriate selection of the equilibrium distribution functions and discrete source terms, we employ a three-distribution-function model based on the passive scalar approach [37,38], in which one represents the velocity field and other two simulate the temperature fields of the fluid and the solid matrix separately. In order to validate the lattice Boltzmann model proposed, three numerical tests are performed to compare with previous results obtained by other methods in the literature.