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Conjugate natural convection heat transfer in an open-ended square cavity partially filled with porous media

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ABSTRACT

Conjugate natural convection heat transfer in an open-ended square cavity, which is partially filled with porous media, is a useful research prototype to deepen our insight into many important practical applications, such as solar energy collectors. But surprising, until now there is no open literature on it. In addition, for traditional numerical approaches, it is a great challenge to model conjugate problems on fluid-porous interfaces. In the present work, firstly we develop a new lattice Boltzmann (LB) approach to overcome such difficulty. The present LB model is validated by three benchmark tests. With the aid of this LB approach, we investigate the effects of thickness of porous layer, fluid-to-porous thermal conductivity ratio and permeability of porous layer on conjugate natural convection heat transfer in an open-ended porous-partially-filled square cavity, for the first time. It is found that these factors all influence the patterns of flow field and temperature field significantly. Especially, there exist some critical values. A small offset from them will cause a substantial change of heat and mass transfer. Sometimes the change trends are completely reversed. The present results may provide useful theoretical guides for the relevant practical applications.

1. Introduction

Natural convection in an open-ended cavity is an important research prototype in thermal science and engineering as it can be used to deepen our insights into many practical applications, such as solar thermal receivers, building ventilation and energy saving [1–3]. Until now there have been numerous publications on this topic. On experimental exploration, recently Montiel-Gonzalez et al. [4] revealed the effects of natural convection and thermal radiation on a solar open cubic cavity-type receiver. The authors observed that variable thermophysical properties of working fluid would influence the results significantly. Natural convection in a horizontal open-ended axisymmetric cavity was investigated experimentally by the holographic interferometry technique [5]. The investigators mapped the isotherms as a function of the temperature on the hot wall and the cavity spacing. Heat transfer in an open-ended vertical eccentric enclosure was reported in [6]. Through analyzing their experimental data, the authors found that the heat transfer coefficient did not change monotonically with the eccentric ratio. Meanwhile, numerical efforts were also carried out. Natural convection of Al_2O_3-water nanofluid in an open-ended enclosure was numerically investigated in [7]. The purpose of [7] was to reveal the influence of magnetic force on heat transfer of nanofluid in an open-ended cavity. Marangoni convection in an open-ended cavity was numerically simulated by Saleem et al. [8]. The authors discussed the effect of thermocapillary forces on natural convection. They also carried out entropy generation analysis. Mohamad et al. [11] studied the influence of aspect ratio on natural convection in open-ended cavities. The numerical results showed the rate of heat transfer deceases asymptotically against increasing of aspect ratio. In [9], the authors considered the scenario where an open-ended cavity was completely filled by porous media. The effects of porosity and permeability of porous media on natural convection were investigated numerically. Boetcher and Sparrow [10] compared some available numerical techniques and stressed the importance of appropriate boundary conditions. Only a few latest studies on this topic are cited here as the total number of the relevant literature is very huge.

In a lot of practical applications, an enclosure is usually partially filled with porous media, e.g. a room with multi-layer building materials [12] or a new type of solar energy receiver [13]. In such scenarios, conjugate heat transfer must be considered appropriately on the interface between porous media and working fluid, which significantly increases the complicity of an investigated domain [14,15]. So far there have been a number of literature on conjugate natural convection heat transfer in an enclosure partially

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Nomenclature

u_α, u_β	fluid velocity (m/s)
p	fluid pressure (N/m^2)
T	temperature (K)
g_α	gravitational acceleration (m/s^2)
R_k	porous-to-fluid thermal conductivity ratio
g_j	pseudo-particle distribution
t	time (s)
c	pseudo-particle speed
e_j	discrete velocity direction of pseudo-particle
n_α	normal direction
Ra	Rayleigh number
Nu	Nusselt number
Da	Darcy number
L	height or length of cavity (m)
d	thickness of porous media (m)
C	heat capacitance, namely the product of density and specific heat capacity (kg^2/K s^2 m)

Greek symbols

ε	porosity of porous media
ν_e	effective kinematic viscosity (m^2/s)
κ_e	effective thermal diffusivity (m^2/s)
σ	porous to fluid heat capacitance ratio
β	thermal expansion coefficient (1/K)
τ_T	dimensionless relaxation time
ω_j	weight coefficient
ϵ	Knudsen number
$\delta_{\alpha\beta}$	kronecker delta

Subscripts and superscripts

f	fluid
porous	porous media
0	reference value
eq	equilibrium status

filled with porous media. Beckermann et al. [16,17] perhaps are the pioneers in this field. They investigated conjugate natural convection heat transfer in a vertical cavity, in which a porous layer was placed. Their experimental and numerical data showed for a high effective-thermal-conductivity porous layer, natural convection in the porous layer was suppressed, while the isotherms bent sharply on the fluid/porous interface. Natural convection in a square cavity in which differentially heated vertical walls were covered with thin porous layers was studied in [18]. It was observed that the main effect of the porous layer was to decrease convective heat transfer. Singh et al. [19] considered a three dimensional domain. Their numerical results indicated that penetration of the fluid into the porous region depended strongly on the Darcy number (Da) and Rayleigh number (Ra). The influence of a horizontal partial porous partition on natural convection in a square cavity was numerically studied in [20]. The authors claimed that the porous partition would have obvious influence on heat transfer if its size was thick enough. Song and his cooperators [21] experimentally studied natural convection within a rectangular enclosure partially filled with an anisotropic porous medium. They also carried out numerical simulation to reveal the effect of anisotropic permeability on heat transfer characteristics. Natural convective heat transfer from a cylinder in an enclosure partly filled with a porous medium was reported in [22]. Their work showed how the mean heat transfer rate from the cylinder was affected by the size of the fluid gap at the top of the enclosure. Transient natural convection in a cavity partially filled with porous media was investigated, too [23]. In [23], four different configurations were considered to show their influences on the transient processes. As conjugate heat transfer between working fluid and porous media is a challenge for numerical heat transfer research, Arpino et al. [24] tried to developed a more efficient numerical approach to solve the difficulty. Recently, Sheremet and Trifonova [25] numerically investigated unsteady conjugate natural convection in a vertical enclosure partially filled with porous media. The effect of the Darcy number (Da) was discussed in their research. A latest comprehensive review on this topic was presented in [14]. For traditional numerical techniques, to appropriately treat conjugate heat transfer across fluid/-porous interface is a great challenge, especially for complicate geometry [14]. Unfortunately, for numerous practical energy systems, conjugate heat transfer plays an important role [26,27].

Through the above literature survey, it is clear that until now there is no open publication on conjugate natural convection heat transfer in an open-ended enclosure partially filled with porous media, although it is important in energy engineering and civil engineering. The purpose of the present work is to bridge such gap. In the present work, the lattice Boltzmann (LB) method [28] is adopted as a numerical tool to avoid complicated treatments for conjugated fluid/porous interfaces in traditional numerical approaches. Until now there have emerged some research on modelling conjugate heat transfer by the LB method [29–36]. They share a common advantage that interfaces can be treated easily. Karani and Huber [29] proposed a LB model for conjugate heat transfer between fluid flow and solid walls. In their model, any interface between fluid and solid phases was not necessarily treated explicitly. Hu et al. designed a LB model for conjugate heat transfer between fluid flow and solid walls, based on the so-called immersed boundary method to avoid specific treatment on interfaces [30]. An extrapolation LB scheme was developed in [31]. The conjugate heat transfer across curved interfaces can be treated more accurately by their scheme. In [32], the concept "enthalpy" in thermodynamics was introduced to simplify the treatment of conjugate heat transfer on interfaces between fluid and solid. Pareschi and his cooperators [33] extended the so-called Grad's boundary treatment to deal with conjugate heat transfer. Lu et al. [34] found out a different way to deal with conjugate heat transfer between fluid and solid phases. In their LB model, a correction step was introduced to reflect the effect of interfaces on heat flux. The LB models for conjugate heat transfer between porous media and solid walls were presented in [35,36]. A brief review on the advantages and disadvantages of the available LB models for conjugate heat transfer can be found in [32,36]. Obviously, the available LB models all do not cover the topic of conjugate fluid/porous interface with arbitrary heat capacitance ratio (heat capacitance C is the product of density and specific heat capacity). Therefore, the purpose of the present study is twofold: Firstly, a new LB model is proposed to remedy the shortcoming. Secondly, with the aid of this new LB model, the effects of thickness of porous layer, fluid-to-porous thermal conductivity ratio and permeability of porous layer on the characteristics of natural convection heat transfer in an open-ended porous-partially-filled square cavity are discussed for the first time.

2. Governing equations

The governing equations for heat transfer in an open-ended enclosure, where porous media and pure fluid coexist, can be written as [14,25]