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Simulation of conjugate heat transfer between fluid-saturated porous media and solid wall

Sheng Chen[a,b,*]

[a] Institute for Modelling and Simulation in Fluodynamics, Nanoscience and Industrial Mathematics "Gregorio Millán Barbany", Universidad Carlos III de Madrid, Leganes 28911, Spain

[b] Faculty of Engineering, The University of Nottingham, University Park, Nottingham NG7 2RD, UK

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ABSTRACT

Conjugate heat transfer between fluid-saturated porous media and solid walls is an important issue in many disciplines. For traditional numerical techniques, it is still a great challenge to treat conjugate problems, especially with complicated interfaces. In the present work, a new numerical approach, based on the lattice Boltzmann (LB) method, is proposed to address such challenge. In the present approach no explicit special treatment on coupled interfaces between fluid-saturated porous media and solid walls is required. Moreover, no additional source term, which exists in the available LB models, is required. It can guarantee that the simplicity, accuracy and stability of the present model are better than those models. The accuracy and reliability of the present approach are validated by three nontrivial benchmark tests. The excellent agreement with previous published data demonstrates its feasibility and simplicity for modelling conjugate heat transfer with complicated interfaces between fluid-saturated porous media and solid walls. The present work takes a single-relaxation-time model for example to address conjugate heat transfer problems and its multiple-relaxation-time counterpart can be established straightforwardly in the same way.

1. Introduction

Conjugate heat transfer between fluid-saturated porous media and solid walls is an important issue in many disciplines, such as environment and building engineering, energy engineering and biomedical engineering, since in many applications of these disciplines fluid-saturated porous media and solid walls co-exist [1–3]. At the beginning, conjugate heat transfer problems were solved by some (semi)empirical criteria as then no other available tool [4]. With the rapid development of computer science, modern conjugate heat transfer models, based on strictly mathematical descriptions, have been established to replace the (semi)empirical analogies [5]. Originally, conjugate heat transfer was numerically treated as a coupling type of the Dirichlet and Neumann boundary conditions [6]. By such treatment, a compatibility condition should be paid high attention to. Later, it was found a Robin boundary condition treatment may be more useful for some conjugate heat transfer situations [7]. The accuracy and stability of these numerical treatments have been compared recently [8]. One of the keys to affect the accuracy of conjugate heat transfer modelling is the quality of the mesh [9]. However, it was found that even unstructured grids could not meet a extremely complex interface, such as an automobile engine compartment. To address this challenge, many advanced modern techniques, including immersed boundary method [10] and fictitious-domain method [11], are introduced for conjugate heat transfer simulation. So far, numerical simulation has achieved great success in many advanced engineering applications, such as simulating conjugate heat transfer of continuously moving surfaces [12], of compound material [13] and of turbulent forced convection in channels [14]. A comprehensive latest review on this topic has been presented by Dorfman and Renner [5]. Nowadays the fine structures of conjugate heat transfer between fluid-saturated porous media and solid walls also can be predicted exactly with the aid of solving the conjugate heat transfer models numerically. The available literature on numerically modelling conjugate heat transfer between fluid-saturated porous media and solid walls may fall into two categories: (1) solid walls embedded in fluid-saturated porous media and (2) fluid-saturated porous media bounded by solid walls. The industrial background of the former category is heat transfer enhancement of a fin [15,16], while the latter is a popularly adopted research prototype for solar collectors, energy storage systems filled by phase-change materials and so on [17–19]. A latest review on this topic was presented in Ref. [3]. For engineering research, usually fluid-saturated porous media are modelled at the REV (representative

* Institute for Modelling and Simulation in Fluodynamics, Nanoscience and Industrial Mathematics "Gregorio Millán Barbany", Universidad Carlos III de Madrid, Leganes 28911, Spain.
E-mail address: ezzsc2@exmail.nottingham.ac.uk.

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elementary volume) scale (e.g. Refs. [15–19]), due to the balance between necessary macroscopic information and computational cost [20].

Although solving conjugate heat transfer problems numerically is a great breakthrough in thermal science and engineering, it is still a great challenge for the current state-of-art numerical techniques to address conjugate heat transfer problems with complicated interfaces [3,9]. The difficulty stems from the fact that, for the conventional numerical approaches, specific treatments are required to guarantee the continuity of temperature profile and heat flux across the interfaces between fluid-saturated porous media and solid walls [2,3,15–19].

During the past three decades, the lattice Boltzmann (LB) method has attracted increasing attention due to its some intrinsic advantages, such as relatively easy treatment of complicated geometry, high parallel computing efficiency and capturing interaction between different phases at a mesoscopic level [21]. Until now, the LB method has been widely used to investigate heat and mass transfer in porous media [22–25]. Especially, as it is a particle-based numerical solver, the LB method can guarantee, automatically, the continuity of a certain macroscopic quantity and of its flux across an arbitrary interface within the investigated domain, if the macroscopic quantity and its flux can be recovered from the zeroth- and first-order moment of the corresponding pseudo-particle distribution function, respectively. As pointed out by our recent publication [26], this feature may provide a great advantage over the traditional numerical methods for conjugate heat transfer research as in the LB framework one need not explicitly treat the topology of the interface where the conjugated boundary condition should be strictly satisfied [15–19]. So far there have been a number of efforts to model conjugate heat transfer between fluid flows and solid walls by the LB method [27–32]. Recently, the present authors compared the advantages and disadvantages of the available models and then proposed a new LB conjugate model to remedy their drawbacks [33]. However, the efforts to extend the LB method for conjugate heat transfer between fluid-saturated porous media and solid walls at the REV scale are quite sparse. Recently, Gao et al. [34] designed a LB model to simulate conjugate heat transfer in porous media. In their model, an additional source term is added into their LB evolving equation to guarantee to recover the macroscopic energy equation correctly. Unfortunately, their source term includes temporal difference operation, which will hamper numerical stability, code simplicity as well as order of accuracy, as discussed in our work [33].

The purpose of the present work is to bridge the above gap since an efficient REV scale model for conjugate heat transfer between fluid-saturated porous media and solid walls is very crucial in a lot of practical applications, such as solidification processes, modern building thermal insulators and cooling hot intrusions in a geological setting [1,3]. The present work can extend the LB method to these important areas and accelerate the corresponding research, especially where complicated interfaces exist. In many popularly used numerical techniques, such as the finite volume and finite element approaches, a special treatment is required to guarantee the heat flux to be continuous across the interface between two domains with different thermophysical properties [5]. Such treatment will become extremely complicated if the topology of the interface becomes complex, for example irregularly curved interfaces [9]. As stressed in a recent brief review [9], to simulation conjugate heat transfer problems with complex interfaces is still a significant challenge even for the mature numerical techniques. Fortunately, in the LB framework such treatment can be avoided [33]. Compared with previous models, such as Gao's LB model [34] and Chen's LB model [33] for conjugate problems, there is no additional source term in the present scheme, which can guarantee that simplicity, accuracy and stability of the present model are better. The rest of the present paper is organized as follow. In Section 2, the macroscopic governing equations for conjugate heat transfer between fluid-saturated porous media and solid walls, at the REV scale, are presented. Then we will show how to establish a simple numerical approach, based on the LB method, to model such conjugate heat transfer problems. In the present approach, the complexity to explicitly treat the interfaces between fluid-saturated porous media and solid walls, which is a great challenge for the popularly used numerical methods [1–3,15–19], can be avoided. Numerical validation for the present model is conducted in Section 4, followed by a conclusion on this work. What should be emphasized is although in the present work only a single-relaxation-time LB model is presented, its multiple-time-relaxation counterpart can be constructed in the same way, for example based on the MRT REV scale porous model by Liu et al. [35].

2. Governing equations for conjugate heat transfer between fluid-saturated porous media and solid walls

The macroscopic governing equation for heat transfer in fluid-saturated porous media, at the REV scale, reads [1,2,36]:

$$\sigma\partial_t T + \nabla_\alpha T u_\alpha = \nabla_\alpha \kappa_m \nabla_\alpha T. \tag{1}$$

where u_α and T are the volume-averaged velocity and temperature of fluid in the saturated porous media, respectively. The parameter $\sigma = \varepsilon + (1-\varepsilon)C_s/C_f$, where ε is the porosity of the porous media, and C_s and C_f are the heat capacitance (the product of density and heat capacity) of solid porous matrix and of saturating fluid, respectively. In addition, $\kappa_m = \lambda_m/C_f$ is the effective thermal diffusivity of fluid-saturated porous media, where λ_m is the corresponding effective thermal conductivity. Bear in mind Eq. (1) is valid only when solid porous matrix and saturating fluid meet the thermal equilibrium restriction. If not, the governing equations for heat transfer in porous media should be modified to consider the thermal non-equilibrium effect [37]. For thermal non-equilibrium cases, besides Eq. (1), meanwhile an additional heat conduction equation for solid porous matrix should be solved and Gao et al. developed a LB model for such cases [37]. The method proposed in the present paper to deal with conjugate heat transfer between fluid-saturated porous media and solid wall will not be affected by the alteration of the governing equations for heat transfer in porous media, so the present method can still work well for simulating conjugate heat transfer between fluid-saturated porous media and solid wall considering the thermal non-equilibrium effect if Gao's LB model [37] is adopted to replace Guo's LB model [36] used in this work.

For solid walls, the macroscopic governing equation for temperature field reads [1–3]:

$$\partial_t T = \nabla_\alpha \kappa_s \nabla_\alpha T. \tag{2}$$

where $\kappa_s = \lambda_s/C_s$ is the thermal diffusivity of solid walls, where λ_s and C_s are the thermal conductivity and heat capacitance of solid walls.

For conjugate heat transfer scenarios, on the interfaces between fluid-saturated porous media and solid walls, the following restrictions should be satisfied [1–3]:

$$T_+ = T_- \tag{3}$$

$$n_\alpha[\lambda_m \nabla_\alpha T]_+ = n_\alpha[\lambda_s \nabla_\alpha T]_- \tag{4}$$

where n_α is normal to the interface, and $[\ \ ]_+$ and $[\ \ ]_-$ indicate the parameters at each side of the interface. For the popularly used numerical methods, specific treatments are required to ensure Eqs. (3)–(4) to be held exactly on the interfaces [2,3,15–19]. Unfortunately, for complicated interfaces, it is a great challenge (sometimes impossible) to identify the normal direction n_α [9,29]. For example, as shown by the Tables 1 and 2 in Ref. [29], there is an extremely complex extrapolation process to identify the normal direction and to evaluate the thermal flux

Table 1
Average Nusselt number on interface.

λ_s/λ_f	0.1	1	5	10
Ref. [2]	0.478	3.433	7.710	9.168
present	0.4897	3.5088	7.9936	9.5366