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An investigation on the body force modeling in a lattice Boltzmann BGK simulation of generalized Newtonian fluids

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HIGHLIGHTS

- A unified framework is devised to compare different LB forcing models.
- The formal equilibrium function appeared in the LB equation should be expanded.
- The CL is the most accurate forcing model for transient simulation.
- The newly devised BG–CL forcing model is best for the steady state simulations.

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ABSTRACT

Body force modeling is studied in the Generalized Newtonian (GN) fluid flow simulation using a single relaxation time lattice Boltzmann (LB) method. First, in a shear thickening Poiseuille flow, the necessity for studying body force modeling in the LB method is explained. Then, a parametric unified framework is constructed for the first time which is composed of a parametric LB model and its associated macroscopic dual equations in both steady state and transient simulations. This unified framework is used to compare the macroscopic behavior of different forcing models. Besides, using this unified framework, a new forcing model for steady state simulations is devised. Finally, by solving a number of test cases it is shown that numerical results confirm the theoretical arguments presented in this paper.

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1. Introduction

The LB simulation of non-Newtonian fluid flows, introduced by Aharonov and Rothman in 1993 [1], started with simulation of the GN fluids for which stress tensor depends only on the current value of the strain rate tensor [2]. The LB method has been successfully employed for simulation of GN fluid in various applications [3–5]. One of the most attractive features of using the LB method for GN fluid problems is its ability in computing strain rate tensor locally without using derivatives of the velocity field [6]. This improves the computational efficiency of simulations since the computation of strain rate tensor is a time consuming step in non-Newtonian flow solvers.

In the LB context, there are two different approaches for simulating GN flows. The conventional approach allows for variations of relaxation parameter in time and space so that desired shear dependent viscosity is achieved [1,7]. Although this approach has been improved in the last two decades [8–10], it cannot get rid of instabilities which may arise when the value of relaxation parameter becomes high or approaches 0.5 during simulations even if a multiple relaxation time LB method is employed [11]. The second approach utilizes a fixed value for the relaxation time parameter [12,13]. To achieve

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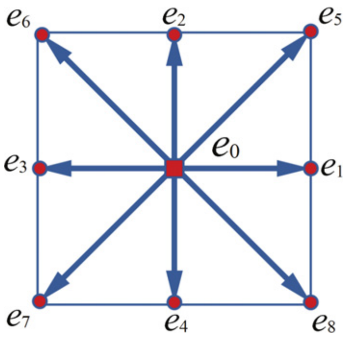

Fig. 1. A D2Q9 lattice and its relevant parameters. The lattice central node(site) is shown by a square symbol at position **x** while its 8 neighboring sites located at $\mathbf{x} + \mathbf{e}_i \Delta t$ are shown by circles. Also, the spacing between each site and its nearest neighbor is a lattice unit.

this goal, recently, it was proposed that non-Newtonian effects in the macroscopic equations be modeled by definition of a proper body force at the expense of losing local computation [13]. This approach is followed in the present paper since it keeps the structure of the LB method unchanged; yet, the incorporation of body force in the LB method appears to be a non-trivial task.

Several forcing models exist in the literature [14–20] which can be employed in the LB method for GN flow simulations using a body force. A number of researchers have compared different models and predicted the accuracy of these forcing models in the macroscopic level [21–23,18–20]. In the authors view, the use of different models with different test cases has made it difficult to judge the appropriateness of each model in specific problems. In the extreme case, one might find some statements in different papers contradictory. For instance, two seemingly conflicting statements exist concerning three frequently used body force modelings which have been proposed by Buick and Greated (BG model) [18], Guo et al. (GZS model) [19], and Cheng and Li (CL model) [20]. Firstly, it has been stated that the BG model should be used for steady state simulations while the GZS model should be used for transient studies [22]. On the other hand, it has been shown that in some applications, both the BG and GZS models produce almost identical numerical results [24]. Secondly, in some applications it has been shown that the CL model is more accurate than the GZS model [25] while elsewhere it has been emphasized that GZS and CL are identical [26]. Clarifying these ambiguities is the main goal of this paper.

In this paper, first the LB governing equations are presented for the GN flow simulations using body force. Then, by studying the LB simulation of a shear thickening Poiseuille flow, the BG, GZS, and CL models are compared and the ambiguities in the literature are explained. In the next step, a parametric study is performed in which the macroscopic behaviors of different body force modelings in both steady state and transient simulations are compared. Finally, a number of test cases are solved to confirm the theoretical arguments.

2. Governing equations

In this paper, the LB simulation of GN fluids is performed by employing a body force. First, a body force is defined in the macroscopic level. That is, the non-Newtonian term in the macroscopic equations are included in this body force and the remaining terms of macroscopic equations are rearranged so that for $(\alpha, \beta = 1, 2)$ the Navier–Stokes Equations (NSE) are Q3 obtained as in Ref. [13]

$$\begin{aligned} &\partial_t u^*_\beta + \partial_\alpha (u^*_\alpha u^*_\beta) = -\frac{1}{\rho}\partial_\beta p + 2\nu \partial_\alpha (S_{\alpha\beta}) + F_\beta, \\ &F_\beta = 2(\nu_{nn} - \nu)\partial_\alpha S_{\alpha\beta}, \\ &S_{\alpha\beta} = \frac{1}{2}(\partial_\alpha u^*_\beta + \partial_\beta u^*_\alpha), \end{aligned} \tag{1}$$

in which p, ρ, u^*_β, ν, and $S_{\alpha\beta}$ are fluid pressure, fluid density, the velocity component in β direction, constant shear viscosity, and the strain rate tensor, respectively. Moreover, ν_{nn} is the non-Newtonian shear dependent viscosity which is modeled for each GN fluid.

In the following, it is explained how to derive a LB equation which can properly represent Eqs. (1). The LB method describes evolution of a discretized single particle distribution function $f_i(\mathbf{x}, t)$ which is simply called distribution function, hereafter. Distribution function $f_i(\mathbf{x}, t)$ represents density of particles with the lattice basis velocity $\mathbf{e}_i$ at specific position $\mathbf{x}$ and time t. There are different discretization forms for the distribution function in terms of space and velocity. A two-dimensional discretization called D2Q9, shown in Fig. 1, is used in the present paper without loss of generality in the following theoretical analysis.

It is proven that the analysis of forcing models is unaffected by using different collision models in the LB method [23]. Therefore, for the sake of brevity, in this paper, the so-called single relaxation time LB method of Bhatnagar–Gross–Krook

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