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Numerical investigation of two-component jet flow with heat transfer in a channel by lattice Boltzmann method

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ABSTRACT

The two-component jet flow with heat transfer in a channel is numerically investigated by the pseudo-potential lattice Boltzmann method using discretized force treatment coupled with passive-scalar approach. The influences of interaction strength, Reynolds number and Prandtl number of jetting and surrounding fluids on jet flow with heat transfer in a channel are analyzed. Numerical results show that the extrusion effect, which derives from these influence factors, is prominent for fluid distribution and flow.

1. Introduction

Jet flow we are concerned with in this article is an efflux of fluid that is projected into another surrounding fluid, which widely exists in engineering industries, aerospace applications and process industries [1–3]. Such a thermal two-component fluid-fluid flow is always a hard task in computational fluid dynamics (CFD). For example, complex components diffusion, the generation and moving of a large number of small scattered the interface between fluids are quite difficult for the conventional CFD methods. Recently, the lattice Boltzmann method (LBM) has shown great potential in simulating complex fluid systems [4–9], especially in multicomponent and multiphase flow [10–15]. In fact, the macro dynamic behavior of multicomponent and multiphase fluid flow is a macro view of the micro interaction between components or phases. The microscopic nature and mesoscopic characteristics of LBM make it be able to directly describe this micro interaction.

Several lattice Boltzmann (LB) approaches have been proposed to describe multicomponent and multiphase flows [16–19]. The pseudo-potential approach developed by Shan and Chen is based on pairwise molecular interactions [17,20,21]. Once the interactions are properly chosen, spontaneous separation between the different fluid components occurs. This is one of the most successful LB multicomponent and multiphase approaches due to its ease implementation [22,23]. In previous work, we showed the advantage of pseudo-potential LBM compared to the conventional volume-of-fluid method in simulating jet flow, including its ability for describing the repulsive forces and the transition region between different fluids. We also improved pseudo-potential approach by using discretized force treatment for higher numerical stability [24].

In this paper, double-distribution-function approach [25–28], in which density field and temperature field are described by different LB equations, is used to realize the heat transfer. The pseudo-potential approach using discretized force treatment is adopted for density field. For temperature field, the passive-scalar approach is chosen because of its simple in form, numerical stability and accuracy [25,26,28]. Effect of interaction strength, Reynolds number and Prandtl number of jetting and surrounding fluids on jet flow with heat transfer in a channel are investigated.

The remaining part of this paper is organized as follows. In Section 2, the double-distribution-function LB model is described. In Section 3, the LB model is validated to be suitable for jet flow with heat transfer in this paper. In Section 4, numerical simulations and results are presented and discussed. Finally, conclusions are drawn in Section 5.

2. Numerical model

The double-distribution-function LBM is adopted in this article for jet flow with heat transfer. The pseudo-potential approach with discretized force treatment for density field and the passive-scalar approach for temperature field will be described in this section.

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2.1. Density field

In the pseudo-potential LBM [17], state of all the component fluids are described by the velocity distribution $f_\alpha^\sigma(\mathbf{x},t)$, which indicates the number of fluid particles belonging to the component σ with velocity $\mathbf{e}_\alpha$ at node $\mathbf{x}$ and time t. The temporal evolution equation of $f_\alpha^\sigma(\mathbf{x},t)$ is the LB equation, which can be derived as a discrete Boltzmann equation so that the velocity space is discretized in addition to physical space and time. The multicomponent discrete Boltzmann with discretized force $F_\alpha^\sigma(\mathbf{x},t)$ is given as follow [24]:

$$f_\alpha^\sigma(\mathbf{x}+\mathbf{e}_\alpha\delta t, t+\delta t) - f_\alpha^\sigma(\mathbf{x},t) = -\frac{1}{\tau_f^\sigma}\left[f_\alpha^\sigma(\mathbf{x},t) - f_\alpha^{\sigma,eq}(\mathbf{x},t)\right] + F_\alpha^\sigma(\mathbf{x},t)\delta t, \tag{1}$$

where δt is the time step, $f_\alpha^\sigma(\mathbf{x},t)$ is the equilibrium distribution function and τ_f^σ is the collision relaxation time, which has the relationship with kinematic viscosity ν^σ as:

$$\nu^\sigma = \frac{2\tau_f^\sigma - 1}{6}\frac{(\delta x)^2}{\delta t}, \tag{2}$$

where δx is the lattice step, and $c = \delta x/\delta t$ is the lattice speed.

The equilibrium distribution function $f_\alpha^{\sigma,eq}$ is given by:

$$f_\alpha^{\sigma,eq} = \omega_\alpha \rho^\sigma\left[1 + \frac{\mathbf{e}_\alpha\cdot\mathbf{u}^{eq}}{c_s^2} + \frac{(\mathbf{e}_\alpha\cdot\mathbf{u}^{eq})^2}{2c_s^4} - \frac{(\mathbf{u}^{eq})^2}{2c_s^2}\right], \tag{3}$$

where the values of weighting coefficient ω_α, discrete velocity $\mathbf{e}_\alpha$ and sound speed c_s are related to form of lattices, and we choose D2Q9 model, which is the widely used in two-dimensional simulations. For D2Q9 model, ω_0=4/9, ω_α=1/9 $(\alpha = 1-4)$, ω_α=1/36 $(\alpha = 5-8)$;$\mathbf{e}_0 = (0,0)$, $\mathbf{e}_\alpha = c(\cos[(\alpha-1)\pi/2], \sin[(\alpha-1)\pi/2])$ $(\alpha = 1-4)$, $\mathbf{e}_\alpha = \sqrt{2}c(\cos[(2\alpha-1)\pi/4], \sin[(2\alpha-1)\pi/4])$ $(\alpha = 5-8)$; and $c_s = c/\sqrt{3}$. In additions, ρ^σ is the local density of the component σ, which can be calculated by $\rho^\sigma = \sum_\alpha f_\alpha^\sigma$, and $\rho = \sum_\sigma \rho^\sigma$ is the total density of the mixture fluid. Besides, since the total momentum of particles of all components should be conserved, the effective flow velocity of mixture fluid $\mathbf{u}^{eq}$ is calculated by:

$$\mathbf{u}^{eq} = \frac{\sum_\sigma \rho^\sigma \mathbf{u}^\sigma/\tau_f^\sigma}{\sum_\sigma \rho^\sigma/\tau_f^\sigma}, \tag{4}$$

where the flow velocity $\mathbf{u}^\sigma$ for each components are obtained as:

$$\rho^\sigma \mathbf{u}^\sigma = \sum_\alpha f_\alpha^\sigma \mathbf{e}_\alpha + \frac{1}{2}\mathbf{F}^\sigma\delta t. \tag{5}$$

The force term $\mathbf{F}^\sigma$ here is the interparticle force in the pseudo-potential approach, and it is defined as the sum of all interparticle forces between particles at node $\mathbf{x}$ and its surrounding nodes $\mathbf{x}'$[17]:

$$\mathbf{F}^\sigma(\mathbf{x}) = -\psi^\sigma(\mathbf{x})\sum_{\mathbf{x}'}\sum_{\overline{\sigma}} G_{\sigma\overline{\sigma}}(\mathbf{x},\mathbf{x}')\psi^{\overline{\sigma}}(\mathbf{x}')(\mathbf{x}'-\mathbf{x}), \tag{6}$$

where the effective density $\psi^\sigma(\mathbf{x})$ is defined as a function of the density of the σth component at node $\mathbf{x}$, and we choose $\psi^\sigma(\mathbf{x}) = \rho^\sigma(\mathbf{x})$ in this work [29]. $G_{\sigma\overline{\sigma}}(\mathbf{x},\mathbf{x}')$ controls the strength of the interaction potential between components σ and $\overline{\sigma}$. For a D2Q9 model, $G_{\sigma\overline{\sigma}}(\mathbf{x},\mathbf{x}')$ is given by $G_{\sigma\overline{\sigma}}(\mathbf{x},\mathbf{x}') = g^{\sigma\overline{\sigma}}(|\mathbf{x}-\mathbf{x}'|=1)$ and $G_{\sigma\overline{\sigma}}(\mathbf{x},\mathbf{x}') = g^{\sigma\overline{\sigma}}/4(|\mathbf{x}-\mathbf{x}'|=\sqrt{2})$. Phase separation between components occurs automatically when the interaction strength $g^{\sigma\overline{\sigma}}$ are properly chosen. Besides, $g^{\sigma\overline{\sigma}}$ can control the mutual solubility of components.

The forcing scheme plays an important role in the pseudo-potential LB model [30,31]. The shortage of the original pseudo-potential model is due in large part to Shan-Chen's forcing scheme. This interparticle force $\mathbf{F}^\sigma$ is now introduced to Eq. (1) after being discretized according to velocity space, and the discretized force term can be express as [32]:

$$F_\alpha^\sigma = \left(1 - \frac{1}{2\tau_f^\sigma}\right)\omega_\alpha\left[\frac{\mathbf{e}_\alpha - \mathbf{u}^{eq}}{c_s^2} + \frac{\mathbf{e}_\alpha\cdot\mathbf{u}^{eq}}{c_s^4}\mathbf{e}_\alpha\right]\cdot\mathbf{F}^\sigma. \tag{7}$$

This force treatment makes pseudo-potential LBM more stable and accurate than the original one mainly due to the smaller spurious velocity [24]. Of course, this treatment can not let the multi-component fluid model handle large quantities contrasts without compromising stability and accuracy of the numerical solutions, since the spurious velocity still exists. For example, we have tested that the maximum of viscosity ratio for static bubble case is 4510, in which the relaxation parameter τ of fluid in the bubble is 5.01 and the one out of the bubble is 0.501.

$\tau = 5.01$ is, however, significantly larger than the typical range used for τ in LBM simulations. $\tau > 0.5$ is necessary to ensure the numerical stability of the LBM simulations [33] and $\tau = <1.0$ is typically used for numerical accuracy of the results [40,41]. Although LBM simulations with $\tau > 1.0$ were previously reported in the literature [34,40], caution should be taken for numerical accuracy of the results for $\tau > 1.0$.

The total flow velocity of mixture fluid is given by:

$$\mathbf{u} = \frac{\sum_\sigma \rho^\sigma \mathbf{u}^\sigma}{\sum_\sigma \rho^\sigma}. \tag{8}$$

The treatment here is different from the model presented by Porter et al. [34] in that we use Guo et al.'s forcing scheme, whereas Porter et al. use He et al.'s [35]. He et al.'s forcing scheme comes from continuous Boltzmann equation. It assumes that distribution function can be approximated as equilibrium distribution, which is without rigorous proof. Besides, both the redefined equilibrium distribution function and the forcing term contain terms of order u^3, which is inconsistent with the whole system. On the other hand, Guo et al.'s forcing scheme is based on expansion method of particle velocity, and its parameters are determined by Chapman-Enskog analysis. It can lead to the exact Navier-Stokes equations [32].

2.2. Temperature field

The passive-scalar approach neglects the viscous heat dissipation and compression work carried out by the pressure, then it satisfies the following equation [25,26]:

$$\frac{\partial T}{\partial t} + \nabla\cdot(\mathbf{u}T) = \nabla\cdot(\chi\nabla T), \tag{9}$$

where χ is the thermal diffusivity and T is temperature. The evolution equation of the temperature distribution function T_α is as follow:

$$T_\alpha(\mathbf{x}+\mathbf{e}_\alpha\delta t, t+\delta t) - T_\alpha(\mathbf{x},t) = -\frac{1}{\tau_T}\left[T_\alpha(\mathbf{x},t) - T_\alpha^{eq}(\mathbf{x},t)\right], \tag{10}$$

where temperature equilibrium distribution function $T_\alpha^{eq}(\mathbf{x},t)$ is given by:

$$T_\alpha^{eq} = \omega_\alpha T\left[1 + \frac{\mathbf{e}_\alpha\cdot\mathbf{u}}{c_s^2} + \frac{(\mathbf{e}_\alpha\cdot\mathbf{u})^2}{2c_s^4} - \frac{\mathbf{u}^2}{2c_s^2}\right]. \tag{11}$$

τ_T is temperature relaxation time for the mixture fluid, which depends on density of components, and it can be calculated by [28]:

$$\tau_T = \sum_\sigma \frac{\rho^\sigma \tau_T^\sigma}{\rho}, \tag{12}$$

where τ_T^σ is temperature relaxation time of the component σ. In addition, τ_T has the relationship with thermal diffusivity χ as:

$$\chi = \frac{2\tau_T - 1}{6}\frac{(\delta x)^2}{\delta t}. \tag{13}$$