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Numerical investigation of a gas–solid turbulent jet flow with Reynolds number of 4500 using lattice Boltzmann method

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ABSTRACT

The gas–solid two-phase turbulent plane jet flow with high Reynolds number of 4500 was numerical investigated by means of lattice Boltzmann method (LBM). The multiple relaxation time (MRT) was employed to deal with the high Reynolds number fluid flows, and the particles were traced by the Lagrangian method. The results show that the flow changes from initial symmetric mode to asymmetric mode with the development of the flow. And asymmetric pattern appears first at the position of $x/d = 4$, where the vortex structures begin to form. The dispersion of particles at different Stokes number shows various distributions. The MRT-LBM shows its good ability in simulating turbulent flow with the high Reynolds number.

1. Introduction

The lattice Boltzmann method is originated from Lattice Gas Automata (LGA) [1,2], and it can also be derived directly from the Boltzmann equation [3]. A direct connection between the Boltzmann equation and the incompressible Navier–Stokes equation can be obtained under the condition of near incompressible [4,5]. Compared with the traditional Computational Fluid Dynamics (CFD) such as Navier–Stokes equation, LBM shows distinct advantages of high efficiency of parallel implementation, high calculation efficiency and ability in dealing with moving and complex boundaries [6–9]. LBM is a relatively new computational fluid method, and it has attracted considerable attention in recent years.

Over the past decade, LBM has been widely used in scientific research and engineering application. Shan and Chen [10] developed a lattice Boltzmann model to simulate flows containing multiple phases and components, and this model presented many applications in large-scale numerical simulations of various types of fluid flows. Park et al. [11] applied the lattice Boltzmann method to simulate the flow in the electrode of a PEM fuel cell. Succi [12] employed the LBM successfully to calculate a variety of configurations, even those with a complex coupling of physical and chemical processes. Chen et al. [13] carried out simulations of complex fluid physics such as cars and airplanes using an extended kinetic Boltzmann equation, analyzing different approaches based on extensions of the Boltzmann equation. Han et al. [14] and Feng et al. [15] presented a new solution strategy that coupled lattice Boltzmann (LB), large eddy simulation (LES), and discrete element (DE) methodologies to simulate particle–fluid systems at moderately high Reynolds numbers.

Enhanced collision operator was presented to be an efficient strategy for the lattice gas Boltzmann equation by Higuera et al. [16]. Then the multiple relaxation time (MRT) is developed and used widely. McCracken and Abraham [17] developed a MRT lattice-Boltzmann model for multiphase flow and evaluated the accuracy in several test problems such as oscillating

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liquid cylinders and capillary waves. Pan et al. [18] conducted a comparative study of the LBE models with MRT and the BGK-SRT, and reported that the MRT–LBE model is superior to the BGK–LBE model. Guo and Zheng [19] simulated the Poiseuille flow in the slip flow regime by the lattice Boltzmann equation (LBE) with multiple relaxation times (MRTs). Yu et al. [20] carried out the application of multiple-relaxation-time (MRT) lattice Boltzmann equation (LBE) for large-eddy simulation (LES) of the turbulent square jet flow. The MRT-LBE model for LES was carried out in a surface mounted cube in a channel at Re = 40,000 by Krafczyk et al. [21], and their preliminary results agree well with experimental data. Dynamic subgrid scale (SGS) models were incorporated in the MRT-LBM of LES of fully-developed turbulent channel flow at two different shear Reynolds numbers of 180 and 395, reported by Premnath et al. [22]. General lattice Boltzmann equation (GLBE) using MRT with forcing term for eddy capturing simulation of wall-bounded turbulent flows was presented by Premnath et al. [23], they found that markedly stability characteristics and good agreements were achieved.

Deep understanding of the flow coherent structures and particle dispersion in the turbulent jet is of great significance in efficient engineering applications in the fields of chemical reaction and jet combustion [24]. The particle dispersion is an important factor in the engineering design and efficient engineering applications.

The turbulent jet has been studied for a long time. Bradbury used a hot-wire anemometry to measure the statistical quantities in the self-similar region of a plane jet, and observed that the initial and external conditions have a strong influence on the development of the plane jet flow fields [25]. Stanley and Sarkar [26] investigated the 2D single-phase flow in the plane jet by direct numerical simulation. There are also many experimental and numerical studies reported on the gas–solid two-phase turbulent jet flows. Melville and Bray [27] investigated the two-phase turbulent jet flows and presented a model to describe them. Tsuji et al. [28] measured axisymmetric particle-laden jets by three different devices, and particle and air velocities, particle concentration and air turbulence were obtained. Despirito and Wang [29] numerically studied the influence of the particle Stokes number on the flow stability in the two-way coupled particle-laden jet, and found that the particles at Stokes numbers on the order of 1 correspond to the maximum flow stability. Fan et al. [24] investigated the gas-particle two-phase flow in the 2D turbulent plane jet by solving the compressible flow fields using direct numerical simulation, and they focused their study on the evolution of coherent vortex structures and dispersion patterns of particles in the near field. Menon and Soo [30] developed a three-dimensional lattice Boltzmann equation solver to study flows associated with synthetic jets and turbulent-forced rectangular jets by large-eddy simulation (LES). Premnath and Abraham [31] investigated the transient and incompressible turbulent plane jets by the discrete lattice BGK Boltzmann equation, and a spatially and temporally dependent relaxation time parameter is used to represent the averaged flow field, satisfactory results is obtained.

However, there are few studies reported about the particle dispersion and large-scale vortex structures in the gas–solid two-phase turbulent jet flow with the moderately high Reynolds numbers using LBM. In addition, most of the numerical studies mentioned above were based on Navier–Stokes equation. In this paper, we use the LB method to investigate the vortex characteristics and the particle dispersion patterns in a 2D gas–solid turbulent plane jet. The MRT-LBM was employed to deal with the high Reynolds number fluid flows. The main objective of this study is to study the evolution of the coherent structures and the dispersion of particles at different Stokes numbers by the means of MRT-LBM, and the particles were traced by the Lagrangian method.

The Letter is organized as follows. In Section 2 we describe the lattice Boltzmann method. Section 3 introduces the governing equations for particles. Section 4 presents the computational conditions. The numerical results and discussions are given in Section 5. The last section is devoted to conclusions.

2. D2Q9 MRT-LBE model

Lattice BGK (LBGK) model and D*n*Q*b* (*n* is the dimension of the space and *b* is the discretized speed) model presented by Qian et al. [32]. On each node of the lattice, there are a set of symmetric discrete velocities $\{e_i|i = 0, 1, \cdots, b-1\}$ and a set of a velocity distribution functions $\{f_i|i = 0, 1, \cdots, b-1\}$. In this paper, direct simulation using LBM is carried out to study the turbulent jet flow, large eddy simulation (LES) is not considered. A nine velocities two dimensional (D2Q9) LBE model coupled with multiple relaxation time (MRT) [32,33] was employed. The evolution equation for D2Q9 LBM could be described as:

$$\boldsymbol{f}(\boldsymbol{x} + \boldsymbol{e}_i dt, t + dt) - \boldsymbol{f}(\boldsymbol{x}, t) = -S(\boldsymbol{f}(\boldsymbol{x}, t) - \boldsymbol{f}^{eq}(x, t)), \tag{1}$$

where S is the collision matrix, and $S = diag(s_0, s_1, \ldots, s_8)$.$\boldsymbol{f} = (f_0, f_1, \ldots, f_8)^T$ and $\boldsymbol{f}^{eq} = (f_0^{eq}, f_1^{eq}, \ldots, f_8^{eq})^T$ are vectors of the distribution function and their corresponding equilibria, and the T donates the transpose operator. The MRT-LBE equation can be written as follows:

$$\boldsymbol{f}(\boldsymbol{x} + \boldsymbol{e}_i dt, t + dt) - \boldsymbol{f}(\boldsymbol{x}, t) = -M^{-1}S(\boldsymbol{m}(x, t) - \boldsymbol{m}^{eq}(x, t)), \tag{2}$$

where M is a 9×9 transform matrix, and $M^{-1} = M^T(MM^T)^{-1}$. M was used to transform the distribution function to the velocity moments $\boldsymbol{m} = (m_0, m_1, \ldots, m_8)^T$ as follows.

$$\boldsymbol{m} = M \cdot \boldsymbol{f} \quad \text{and} \quad \boldsymbol{f} = M^{-1} \cdot \boldsymbol{m}. \tag{3}$$