Available online at www.sciencedirect.com
ScienceDirect
Journal of Hydrodynamics
2017,29(1):68-74
DOI: 10.1016/S1001-6058(16)60718-7
www.sciencedirect.com/
science/journal/l0016058

Lattice Boltzmann simulations of oscillating-grid turbulence*

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(Received January 7, 2015, Revised August 17, 2015)

Abstract: The lattice Boltzmann method is used to simulate the oscillating-grid turbulence directly with the aim to reproduce the experimental results obtained in laboratory. The numerical results compare relatively well with the experimental data through determining the spatial variation of the turbulence characteristics at a distance from the grid. It is shown that the turbulence produced is homogenous quasi-isotropic in case of the negligible mean flow and the absence of secondary circulations near the grid. The direct numerical simulation of the oscillating-grid turbulence based on the lattice Boltzmann method is validated and serves as the foundation for the direct simulation of particle-turbulence interactions.

Key words: Oscillating grid, quasi-isotropic homogenous turbulence, mean flow, lattice Boltzmann method

Introduction

The turbulence generated from the oscillating-grid is characterized by its zero-mean flow, yielding an approximate homogeneity at some distance away from the grid. The intensity of this homogeneous turbulence can be easily controlled, and thus, it is suitable to use it for investigating some phenomena encountered in hydraulic and environmental engineering[1], such as, the free surface fluctuation[2], the particle suspensions and sedimentation[3], and the sediment transport[4].

Many experiments on the oscillating-grid turbulence were conducted for various research purposes. The approximately homogeneous, zero-mean turbulence can be produced by oscillating a symmetrical grid in a water tank[5,6]. The grid is characterized by the diameter of the grid bars d_g, the mesh size M (defined as the spacing between bars), and the grid solidity σ (defined as the ratio of the area of bars to the total area of the grid). The intensity of the turbulence generated by the oscillating-grid depends on the mesh (d_g, M and σ) as well as the stroke S (the maximum distance of the oscillation) and the frequency f_g. As a rule, to generate a nearly homogenous turbulence of zero-mean flow, the solidity of grid σ should be less than 40%[7], the oscillating frequency[8] should be less than 7 Hz and the measurements should be taken at places 2-3 mesh sizes away[5].

Numerical models were also established for more profound investigations of how to produce homogeneous turbulence by using the oscillating-grid. The direct numerical simulation (DNS)[9], to solve the Navier-Stokes equation numerically, was used to examine the homogeneous turbulence through adding energy continuously and locally into the flow. More models such as those solving the Reynolds Equations

* Project supported by the Science Fund for Creative Research Groups of the National Natural Science Foundation of China (Grant No. 51621092), the National Natural Science Foundation of China (Grant No. 51579171), the Tianjin Program of Applied Foundation and Advanced-Technology Research (Grant No. 12JCQNJC04100) and TH-1A supercomputer.
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by using the k - ε models were also used for the oscillating-grid turbulence. However, there was a long debate in the past as to whether it is appropriate to use a k - ε model to describe the zero-mean-shear turbulence[10]. Therefore, further numerical investigations of the oscillating-grid turbulence are desirable.

The lattice Boltzmann (LB) method[11-13], as a new and effective numerical technique of solving the Navier-Stokes Equation, has been successfully employed in the field of computational fluid dynamics to simulate the turbulent flows, such as the decaying turbulence generated with an initial spectrum and the forced turbulence with a random forcing term[14,15]. For this reason, the LB method can be considered as an alternative of the DNS, if the selected lattice size is small enough. Using the LB method, Djenidi[15] simulated the grid-generated turbulence for a steady mean flow passing through a fixed grid. Although in his study, the turbulence generated by grids is simulated, the use of the mean flow is very different from the use of the oscillating-grid to generate turbulence. This is because the mean flow itself can be a turbulent flow, if the Reynolds number is large. In this study, we simulate the turbulence generated from an oscillating flow through a fixed grid by using the LB method.

1. Numerical methodology

1.1 *Lattice Boltzmann method*

This is a relatively new numerical technique for modeling a physical system response in terms of the dynamics of fictitious particles. In the LB approximation, the fluid is described by the density distribution function $f_i(\boldsymbol{x},t)$, which describes the number of particles at a lattice site x, at the time t, with the discrete particle velocity $\boldsymbol{c}_i$. The hydrodynamic parameters, such as the mass density ρ, the momentum density j, and the momentum flux $\boldsymbol{\Pi}$, can be obtained from this particle distribution as follows[16]

$$\rho = \sum_i f_i\ ,\quad \boldsymbol{j} = \rho u = \sum_i f_i \boldsymbol{c}_i\ ,\quad \boldsymbol{\Pi} = \sum_i f_i \boldsymbol{c}_i \boldsymbol{c}_i \tag{1}$$

The LB equation describes the time evolution of the particle density distribution function $f_i(\boldsymbol{x},t)$, and can be expressed as

$$\frac{\partial f_i}{\partial t} + \boldsymbol{c}_i \cdot \nabla f_i(\boldsymbol{x},t) = \Omega_i(\boldsymbol{f}) \tag{2}$$

where $\Omega_i(\boldsymbol{f})$ is the collision operator, including the lattice Bhatnagar-Gross-Krook (BGK) model, proposed by Ladd[16] and the multiple-relaxation-time (MRT) model[11]. We use the Ladd's model, $\Omega_i(\boldsymbol{f})$ can be constructed by linearizing the local equilibrium $\boldsymbol{f}^{eq}$

$$\Omega_i(\boldsymbol{f}) = \Omega_i(\boldsymbol{f}^{eq}) + \sum_j l_{ij} f_j^{neq} \tag{3}$$

where l_{ij} is the matrix element of the linearized collision operator, the non-equilibrium function $f_j^{neq} = f_j - f_j^{eq}$, and $\Delta_i(\boldsymbol{f}^{eq}) = 0$.

Here we use the so-called D3Q19 topology, a three-dimensional cubic lattice with 19 particle velocity vectors. A suitable form for the equilibrium distribution of the 19 particle distribution model is

$$f_i^{eq} = W_i \rho \left[1 + \frac{\boldsymbol{c}_i \cdot \boldsymbol{u}}{c_s^2} + \frac{(\boldsymbol{c}_i \cdot \boldsymbol{u})^2}{2c_s^4} - \frac{(\boldsymbol{u} \cdot \boldsymbol{u})}{2c_s^2} \right] \tag{4}$$

where $c_s = \sqrt{c^2/3}$ is the speed of sound, c is the particle speed, i.e., $c = \Delta x / \Delta t$, in which Δx is the lattice spacing, and the weighting factors W_i are equal to 1/3 $(i=0)$, 1/18 $(i=1,2,\ldots,6)$ and 1/36 $(i=7, 8,\ldots,18)$ for the other particle, 6 coordinate directions and 12 bi-diagonal directions, respectively.

The macro-dynamical behavior can be obtained from the lattice-Boltzmann equation by a multi-scale analysis, i.e., the Chapman-Enskog expansion[18], using an expansion parameter ε, defined as the ratio of the lattice spacing to a characteristic macroscopic length, the hydrodynamic limit corresponds to $\varepsilon \le 1$. It is shown that the lattice-Boltzmann equation reproduces the Navier-Stokes equations with corrections that are of the orders u^2 and ε^2 [17].

1.2 *Model implementation*

The computational domain with two grids (Grid 1 and Grid 2) can generate turbulence. Free slip boundary conditions are applied on both x - and y - boundaries. A bounce-back boundary is imposed at the grid elements to simulate the no-slip conditions. At the inlet and the outlet, an oscillating flow is specified. If z - direction is the streamwise direction, the velocity can be expressed as $u = 0$, $v = 0$ and $w = w_0 \sin(\omega t)$, in which $\omega = 2\pi f_g$ is the angular frequency and is the characteristic velocity. The oscillating flow is implemented as

$$F_x = 0\ ,\quad F_y = 0\ ,\quad F_z = \rho w_0 \omega \cos(\omega t) \tag{5}$$

This is done by introducing an additional term $F_i(\boldsymbol{x},t)$ [18] in the Boltzmann Eq.(2)