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Analysis of convective heat transfer improved impeller stirred tanks by the lattice Boltzmann method

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ABSTRACT

This paper performs the lattice Boltzmann simulation combined with unknown-index algorithm for the convective heat transfer problems of an impeller stirred tank. Three types of motion of the heating impeller are adopted in this study, including rotation with constant angular velocity, oscillation and oscillating rotation, which are denoted as Types I, II, and III stirrings respectively. Because the flow structures in rotation stirring case are concentric vertical, the heat transfer efficiency of the tank walls is lower than those of the other two types of stirrings. The other two types of stirrings, the flow structures include complex vortices and present better field synergy of the fluid velocity and temperature gradient, which positively contributes to the convective heat transfer efficiency. The results also indicate that a large swing process angle of the impeller with oscillating rotation stirring does not have significant advantage, because the flow phenomena would be similar to that of constant angular velocity stirring case. Basically, the Type III stirred tank can be considered as an improved Type II stirred tank by choosing appropriate process angle.

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1. Introduction

Application of heat transfer enhancement technology is an important issue in engineering problem, because it can improve the efficiency of heat-exchange equipments and consequently reduce the energy consumption. In these methods, agitation is an active scheme which changes the pressure and shear stress of fluid flows by the motion of agitator blade to accelerate the heat and mass mixing efficiency. The agitator is often used to make the homogeneous mixture of different materials, to accelerate the chemical reaction, or to improve the heat transfer efficiency of the heating/cooling process. For example, Ranade et al. [1] used the standard k–ε model to simulate the blades stirred tank with baffles. The result was close to the experimental data. In their work, the effects of mixing time and other influencing factors were analyzed for the agitator design. Derksen and Van Den Akker [2] used the large eddy numerical simulation method to analyze the stirred tank with flat disc blades. The wake flow of the impeller and vortex structure in the flow field were observed and analyzed. Shih et al. [3] simulated a two-dimensional rectangular stirred tank by FLUENT software. Different types of blades and boundary conditions were considered for the heat mixing effect and efficiency. The results also focused on the differences of vortices produced in four corners of the rectangle by different types of stirring blades.

The lattice Boltzmann method (LBM) is a numerical simulation method for solving partial differential equations based on the theory of statistical thermodynamics and kinetics of molecular-based equation. As a mesoscopic method, the LBM is different from macroscopic discretization methods or microscopic molecular dynamics methods. According to the basic macroscopic conservation laws of mass, momentum and energy transport, the lattice Boltzmann equation (LBE) describes the microscopic average movement of molecules, namely the collision and propagation behaviors, on a lattice model. Because the collision term in the Boltzmann equation is in a nonlinear differential-integral form and difficult to be solved, some approximate solutions are proposed. In the LBM, the well-known BGK model which makes the LBE a linearized form is often adopted [4–5]. The LBE was originally used for simulation of the fluid flow because it can be recovered to the Navier–Stokes equations successfully by the Chapman–Enskog expansion [6]. In recent years, the LBM has been widely used for many researches of engineering problems, such as fluid flows, heat transfer problem, chemical reaction, electromagnetic field and so on, especially in the mesoscopic engineering and science such as microfluidics [7].

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In the LBM simulation, the physical quantity is calculated according to the evolution of particle distribution function, which is divided into finite components referred to the specific symmetric velocity set on the lattice nodes. In a time step, the particle distribution components collide on lattice nodes and then propagate to neighbors along the lattice directions. After streaming, new distribution components on lattice nodes are obtained from neighbors in a new time step and cause new local and macroscopic physical properties. In the streaming process, it implies no distributions propagating from the boundary nodes into the computation domain, i.e. certain of distribution functions on boundary nodes remain unknown and need to be solved according to the boundary conditions.

Conventionally, these boundary unknowns can be obtained by the bounce-back rule, which assume the unknown incoming non-equilibrium distribution is equal to that of the opposite direction [8,9]. This boundary treatment scheme is easy to implement even for complicated geometries. However, the bounce-back scheme has second-order accuracy only when the physical boundary is located halfway between the bounce-back row and the first row of inner domain [6]. It will lead to inconsistencies when this LBM model is coupled with other PDE solvers or LBM-like algorithms on the same grid set. Subsequently, other methods for solving boundary unknowns are developed. For instance, Zou and He [10] proposed an analytic method for the velocity and pressure boundary conditions on the inlet/outlet of the flow field. The scheme of velocity condition is also applicable to the straight no-slip and slip walls. But it is difficult to be implemented on complicated geometries. For the curvilinear boundary, Lallemand and Luo [11] used a treatment with combination of the bounce-back scheme and interpolations for the curved boundary conditions. In their study, the boundary moving of a curved boundary is also achieved by an extrapolation formula.

Although the analytic or interpolation method gives a good accuracy on the boundary condition calculation, it is more complicated for programming and time-consuming than the simple bounce-back method. In our previous work [12], we presented an unknown-index algorithm for the LBM to solve unknowns on the boundaries with irregular or fractal geometries. By this algorithm, the programming calculation of complex boundary by analytic or interpolation method can be easily implemented as well as the bounce-back scheme. In this paper, we extended the unknown-index algorithm to curvilinear/moving boundary for the convective heat transfer problems in an impeller stirred tank. The characteristics of flow field and heat transfer phenomena in an isothermal stirred tank are discussed. In this work, three motion types of the heating impeller, including rotation with constant angular velocity, oscillation and oscillating rotation, are studied for enhancement of heat transfer efficiency in the present stirred tank.

2. Lattice Boltzmann method

2.1. The hydrodynamic lattice Boltzmann equation

The kinetic theory of gases represents the evolution of particle density distribution function, f, can be described by the Boltzmann equation as

$$\frac{\partial f}{\partial t} + \vec{v} \cdot \nabla f = -\frac{1}{\tau_v}\left(f - f^{eq}\right), \tag{1}$$

where $\vec{v}$ is the microscopic velocity. The right-hand side term is the BGK relaxation model, in which f^{eq} and τ_v are equilibrium distribution function and relaxation time for local equilibrium respectively. By applying a lattice model of a discrete velocity set, $\vec{e}_\alpha$, the Boltzmann equation of BGK approximation can be discretized in the time and space domain and transformed into the lattice Boltzmann equation as

$$f_\alpha(\vec{r} + \vec{e}_\alpha \Delta t, t + \Delta t) = f_\alpha(\vec{r}, t) - \frac{1}{\tau_v}\left[f_\alpha(\vec{r}, t) - f_\alpha^{eq}(\vec{r}, t)\right], \tag{2}$$

where $f_\alpha(\vec{r}, t)$ is the component of density distribution function in α direction on the lattice node at position $\vec{r}$. The LBE includes the collision and propagation processes of distribution function and can be performed individually in different lattice directions. The macroscopic mass and momentum density are obtained by the relation of

$$\rho = \sum_\alpha f_\alpha, \tag{3}$$

$$\rho\vec{u} = \sum_\alpha \vec{e}_\alpha f_\alpha. \tag{4}$$

This paper proposes the LBM simulation of the unknown-index algorithm combined with the curvilinear moving boundary method to study the hydrodynamic and thermal effects in the impeller stirred tank. In the present work, the stirring blade is in a form of rectangle pillar concentrically to the tank. Therefore, the stirred tank system can be simplified to a two-dimensional case as shown in Fig. 1.

The convenient D2Q9 model in Fig. 2 is used both in flow and temperature field simulation. The lattice velocities shown are defined as

$$\vec{e}_\alpha = \begin{cases} (0, 0), & \alpha = 0; \\ \left(\cos\frac{(\alpha-1)\pi}{2}, \sin\frac{(\alpha-1)\pi}{2}\right)c, & \alpha = 1, 2, 3, 4; \\ \sqrt{2}\left(\cos\left[\frac{(\alpha-5)\pi}{2} + \frac{\pi}{4}\right], \sin\left[\frac{(\alpha-5)\pi}{2} + \frac{\pi}{4}\right]\right)c, & \alpha = 5, 6, 7, 8, \end{cases} \tag{5}$$

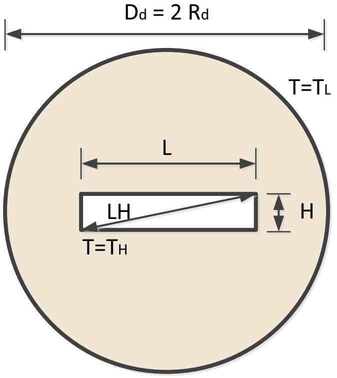

Fig. 1. Simulation model of the impeller stirred tank.

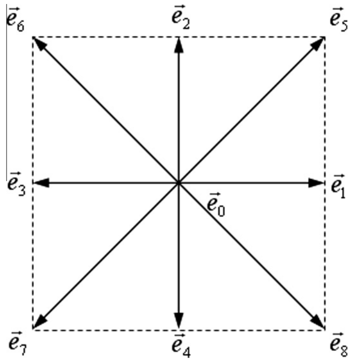

Fig. 2. The D2Q9 model for LBM simulation.

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