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ScienceDirect

Journal of Hydrodynamics

2010,22(3):366-372

DOI: 10.1016/S1001-6058(09)60066-4

www.sciencedirect.com/science/journal/10016058

NUMERICAL STUDY OF WALL WETTABILITIES AND TOPOGRAPHY ON DRAG REDUCTION EFFECT IN MICRO-CHANNEL FLOW BY LATTICE BOLTZMANN METHOD*

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(Received October 12, 2009, Revised March 3, 2010)

Abstract: The dynamics of two-phase flows with a constant driving force inside a micro-channel is studied by using the Lattice Boltzmann Method (LBM) and the Shan-Chen multiphase model in this article. Flow regimes under different wall wettabilities and over smooth and grooved geometric surfaces are investigated. It is found that flow behaviors are strongly affected by the wall wettability and topography. Our results show that the LBM is efficient and accurate, and has very good application prospect in the study of drag reduction of microscopic seepage of reservoir.

Key words: contact angle, wettability, miro-channel, multiphase-flow, Lattice Boltzmann Model (LBM)

1. Introduction

Water injection is the main means of improving oil recovery in low permeability oilfields, but in water flooding development, it mainly behaves with high injection pressure, low injection rate and so on. In order to exploit low permeability reservoir more efficiently, two methods have been used. One is the reservoir reconstruction method, such as acidification, hydraulic fracturing, which reduce drag by amplifying pore size, but the existing problem is that the reservoir may be contaminated if the method is in failure. The other is the surface modification method, which contains drag reductions by surfactant and by hydrophobic nanoparticles (HNPs). The latter is a new drag reduction technology to improve oil recovery in low permeability oilfields in reservoir micro-channels, which can decrease injection pressure and enhance water injection volume. The HNPs are adsorbed by the wall and then a strong- or super-hydrophobic layer is formed, which could lead to a slip boundary condition and decrease drag on the fluid. This mechanism has been modified via lab tests and simulation method by Di et al.[1], but the effects of wall wettabilities and topography on micro-channel flow should be intensively studied.

Droplet motion is a key element of a wide variety of phenomena encountered in technical applications,

* Project supported by the National Natural Science Foundation of China (Grant No. 50874071), the National High Technology Research and Development Program of China (863 Program, Grant No. 2008AA06Z201), the Program of Science and Technology Commission of Shanghai Municipality (Grant No. 071605102), the project of Shanghai Education Commission Research Innovation (Grand No. 08ZZ45), the Program for Changjiang Scholars and Innovative Research Team in Universities (Grant No. IRT0844), and the China Postdoctoral Science Foundation (Grant No. 20090450687).

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such as impact of droplet[2,3], which is used to investigate painting, injection in combustors, ink-jet printing[4] and cooling the hot surface[5], the spreading of mesoscale droplets on homogeneous and heterogeneous surfaces[6], which is used to investigate wetting properties of underlying substrate, and droplet formation[7], which is used to investigate interaction between immiscible fluids. Simulation of the evolution of fluid interface is a challenging problem for both the Lattice Boltzmann Method (LBM) and other conventional CFD techniques, because any phase interface boundary is mesoscopic by nature.

Numerical methods can be very instrumental in enhancing understanding of fluid behavior, the LBM is a promising tool to simulate the incompressible viscous flows[8]. Unlike the traditional CFD, the LBM is based on microscopic models and mesoscopic kinetic equations. The LBM recovers the Navier-Stokes equations in the incompressible flow limit. The LBM can be considered as a mesoscopic approach, lying in between microscopic molecular dynamics and conventional macroscopic fluid dynamics. It does not solve the differential equations, but only involves a series of collision and stream steps. More importantly, it is relatively easy to set the non-slip boundary condition for systems with complex geometry and there are a couple of free surface models[9] developed for simulating the moving interface between immiscible gas and liquid fluids. An alternative solution is the Shan-Chen multiphase model[10,11], which can be useful in treating problems involving surface tension, capillarity and phase transition in multiphase multi-component systems.

In this work, we simulate droplet moving in micro-channel to investigate the effects of wall wettabilities and topography on drag reduction. With a general bounce-back no-slip boundary condition applied to the interface between fluids and solid surfaces, together with the Shan-Chen multiphase model, the LBM is used to simulate the liquid-phase flow inside micro-channels with different wall wettabilities and topography.

2. Numerical model

2.1 *The LBGK model*

The LBM, which involves a single relaxation time in the Bhatnagar-Gross-Krook (BGK) collision operator[12], is used here. The time evolution of this model can be written as

$$f_i\left(\boldsymbol{x}+\boldsymbol{c}_i\Delta t,t+\Delta t\right)-f_i\left(\boldsymbol{x},t\right)=-\frac{1}{\tau}\bullet \left[f_i\left(\boldsymbol{x},t\right)-f_i^{eq}\left(\boldsymbol{x},t\right)\right] \tag{1}$$

where $f_i\left(\boldsymbol{x},t\right)$ is the single-particle distribution function for fluid particles that move in the direction $\boldsymbol{c}_i$ at $\left(\boldsymbol{x},t\right)$, $f_i^{eq}\left(\boldsymbol{x},t\right)$ is the equilibrium distribution function, Δt is time step of the simulation, and parameter τ is the relaxation time characterizing the collision processes, in which the distribution functions relax towards their equilibrium distributions.

As a 2-D nine-particle model, the equilibrium distribution function $f_i^{eq}\left(\boldsymbol{x},t\right)$ depends only on local density and velocity and can be chosen as

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

where

$$\boldsymbol{c}_i=\left(0,0\right)c\,,\quad i=0 \tag{3a}$$

$$\boldsymbol{c}_i=\left[\cos\frac{\left(i-1\right)\pi}{2},\sin\frac{\left(i-1\right)\pi}{2}\right]c\,,\quad i=1,\cdots,4 \tag{3b}$$

$$\boldsymbol{c}_i=\sqrt{2}\left[\cos\frac{\left(2i\text{-}9\right)\pi}{4},\sin\frac{\left(2i\text{-}9\right)\pi}{4}\right]c\,,\quad i=5,\cdots,8 \tag{3c}$$

$$\omega_i=\frac{4}{9},\ i=0 \tag{4a}$$

$$\omega_i=\frac{1}{9},\ i=1,2,3,4 \tag{4b}$$

$$\omega_i=\frac{1}{36},\ i=5,6,7,8 \tag{4c}$$

$$c_s^2=\frac{1}{3}c^2 \tag{5}$$

where $c=\Delta x/\Delta t$ is the lattice velocity, Δx the lattice distance, and Δt the time step of simulation.

The mass density ρ and momentum density $\rho\boldsymbol{u}$ of the fluid are calculated from the first and second moments of the distribution function, i.e.,