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Drag force acting on bubbles in a subchannel of triangular array of rods

Gabor Hazi *, Gusztav Mayer, Attila Markus

MTA KFKI Atomic Energy Research Institute, Theoretical Thermohydraulics Research Group, H-1525 Budapest, Hungary

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ABSTRACT

Forces acting on spherical bubbles in a subchannel of a rod bundle with triangular rod arrangement (the pitch to diameter ratio is $P/D = 1.34$) have been studied at low bubble Reynolds numbers $O(0.1) - O(1)$. The bubble motion has been simulated resolving the interface of the bubble by using the lattice Boltzmann method. Steady drag and virtual mass forces have been determined from the simulation results. Based on the simulation data, the relation $C_D = 16.375/Re_T$ could be established between the steady drag coefficient C_D and the terminal Reynolds number Re_T when the diameter ratio $\lambda = d/D$ of the bubble d and the channel D is less than 0.2. It is found that the virtual mass coefficient can achieve as high value as 7.2, which is a consequence of strong wall effects. Considering interactions between bubbles, cooperation in the axial direction and hindering in the lateral direction could be observed. We demonstrate that the relation between the terminal velocity of a bubble and that of the suspension follows a Richardson–Zaki like correlation, but the exponent is not only a function of the Eotvos and Morton numbers, but it also depends on the particle configuration.

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1. Introduction

For accurate large scale modeling of industrial two-phase flow problems we need reliable models for interfacial mass, momentum and energy transfers. In case of bubble flows, the interfacial momentum transfer is due to the forces acting between the liquid phase and the gas bubbles. The problem of evaluating the hydrodynamic forces acting on a bubble in a fluid is a long standing problem. Models used for predicting forces have usually been developed by some analytical technique applying significant simplifications (inviscid or creeping flow and asymptotic corrections) in order to keep the problem analytically tractable [1]. Then, such models can be adopted to specific flow problems only by tayloring their forms and parameters based on measurement data.

In the last few decades, numerical experiments proved to be good alternatives to real measurements in two-phase flow modeling, just like in many other areas of physics, see e.g. [2,3,5–10,4]. However, a vast majority of studies still focus on basic problems like the study of rising bubble in a periodic box and only a few attempts have been made to get information on bubbly flows in wall bounded geometries, see e.g. [11–13].

In ligth water nuclear reactors, bubbles can appear in the fuel assemblies both in normal and accidental situations. Therefore, the accurate modeling of bubbly flows is vital both from economical and safety point of views. The fuel assemblies of ligth water reactors are usually built up as a regular array of fuel rods and the coolant flows along the rods in the so called subchannels of the assembly. Depending on the actual design, the rods are arranged in a triangular or rectangular array. The bundle is tight, which means that the cross section of the channel is narrow, usually a few square millimeters.

There are many evidences of that forces acting on bubbles in a cylindrical channel depend on the diameter ratio $\lambda = d/D$ of the bubble (d) and the channel (D) as it exceeds 0.06 and 0.12 for low and large Reynolds numbers, respectively [1]. Since the equivalent diameter of a subchannel of a rod bundle is $O(1)$ [mm], therefore wall effects can be expected to be relevant in a subchannel when the bubble diameter is $O(0.1)$ [mm] or larger.

This fact motivated us to perform numerical simulations of bubble motion in a subchannel of a rod bundle and extract information on the hydrodynamic forces acting on the bubbles from the simulation results. A lattice Boltzmann model was developed to simulate the motion of an individual bubble in the subchannel of triangular array of rods resolving the interface of the bubble. Although we have recently used a similar method for the single phase direct numerical and large eddy simulation of turbulent flows in a subchannel [17,18], here, as a first attempt, we shall limit our discussions on laminar flows. In particular, the drag and virtual mass forces are deduced from the simulation results. In our simulations, both the Eotvos and Reynolds numbers are small so the bubble remains spherical. It is demonstrated that the simulations show a consistent picture about the dynamics of bubbles in the subchannel.

* Corresponding author.
E-mail addresses: gah@aeki.kfki.hu (G. Hazi), mayer@aeki.kfki.hu (G. Mayer), amarkus@aeki.kfki.hu (A. Markus).

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In Sections 2 and 3 the numerical method and the simulation results are presented, respectively. Our conclusions are given in Section 4.

2. The lattice Boltzmann method

The lattice Boltzmann method (LBM) is an innovative technique for modeling two-phase flows. Many different models have been developed in the framework of LBM to model bubbly flows see e.g. [2,14–16,5]. In this work the multicomponent–multiphase model of Shan and Chen was adopted [19]. This model has been applied for bubble flow simulations by many authors including the work of Sankaranarayanan et al. [2,3] who simulated bubble dynamics in a periodic box and extracted the drag, virtual mass and lift forces from the simulation results. Since in our problem the domain is wall bounded, there are some small differences between our approach and that of used in [2], nevertheless, for completeness, we briefly review the method we used in our calculations.

To model multicomponent flows, Shan and Chen proposed [19] to solve the lattice Boltzmann equation with Bhatnagar–Gross–Krook collision operator [20]

$$f_i^\sigma(x + c_i\triangle t, t + \triangle t) - f_i^\sigma(x,t) = -\frac{1}{\tau^\sigma}(f_i^\sigma - g_i^\sigma), \tag{1}$$

where $f_i(\mathbf{x},t)$ is the one-particle velocity distribution function, $\mathbf{c}_i$ is the lattice velocity vector, τ^σ is the relaxation time which controls the rate of approach to the local equilibrium $g_i(\mathbf{x},t)$, Δt is the time-step and $\sigma = \{1,2\}$ is for the two components, respectively.

The local equilibrium distribution is written as

$$g_i^\sigma = w_i\rho^\sigma\left[1 + 3c_{i\alpha}u_\alpha^{\sigma,eq} - \frac{3}{2}u_\alpha^{\sigma,eq}u_\alpha^{\sigma,eq} + \frac{9}{2}c_{i\alpha}c_{i\beta}u_\alpha^{\sigma,eq}u_\beta^{\sigma,eq}\right], \tag{2}$$

which is a low Mach number expansion of the Maxwell–Boltzmann distribution.

For the calculations presented in this paper we used a D3Q19 model, for which the lattice velocity vectors $\mathbf{c}_i$ and weights w_i are defined by

$$c_i = \begin{cases} (0,0,0) & i = 0 \\ (\pm1,0,0),(0,\pm1,0),(0,0,\pm1) & i = 1\ldots6 \\ (\pm1,\pm1,0),(\pm1,0,\pm1),(0,\pm1,\pm1) & i = 7\ldots18 \end{cases}$$
$$w_i = \begin{cases} 1/3 & i = 0 \\ 1/18 & i = 1\ldots6 \\ 1/36 & i = 7\ldots18 \end{cases} \tag{3}$$

The density and hydrodynamic velocity of the individual components are defined by

$$\rho^\sigma = \sum_i f_i^\sigma, \quad u_\alpha^\sigma\rho^\sigma = \sum_i c_{i\alpha}f_i^\sigma. \tag{4}$$

The velocity used in the equilibrium distribution function (2) is calculated from

$$u_\alpha^{\sigma,eq} = u'_\alpha + \frac{\tau}{\rho^\sigma}F_\alpha^\sigma, \tag{5}$$

where

$$u'_\alpha = \frac{\sum_\sigma \rho^\sigma/\tau^{\sigma\sigma}u_\alpha}{\sum_\sigma \rho^\sigma/\tau^\sigma}, \tag{6}$$

and the force F_α^σ will be defined later on.

Since we represent two-phases of a single component fluid by two components, we also define the macroscopic quantities of the mixture as

$$\rho = \sum_\sigma \rho^\sigma, \quad \rho u_\alpha = \sum_\sigma \rho^\sigma u_\alpha^\sigma + \frac{1}{2}\Delta t F_\alpha, \tag{7}$$

where

$$F_\alpha = \sum_\sigma F_\alpha^\sigma. \tag{8}$$

It can be shown that the mesoscopic evolution of the particle distribution functions (1), yields the macroscopic equations [21]

$$\partial_t u_\alpha + u_\beta\partial_\beta u_\alpha + \frac{1}{\rho}\left[\partial_\alpha(\rho c_s^2) - \sum_\sigma F_\alpha^\sigma\right] = \nu\partial_\beta^2 u_\alpha, \tag{9}$$

with some error terms, which can be neglected at low Mach numbers or can be partially compensated at higher velocities [22].

That is we solve the Navier–Stokes equations in which the viscosity is given by

$$\nu = c_s^2\sum_\sigma x^\sigma\left(\tau^\sigma - \frac{1}{2}\right), \tag{10}$$

where $x^\sigma$is the mass fraction of the component σ.

In order to model non-ideal gases, surface tension, etc. we need to choose a proper form for F_α^σ. Shan and Chen proposed to calculate the force as the gradient of particle interaction potentials ψ [19]. In this work the same methodology was used, but a new form of the interaction potential was implemented:

$$\psi^{(1)} = \frac{\rho^{(1)}}{T + C_1\rho^{(1)}} \tag{11}$$

because it can be shown analytically, that using this potential Maxwell equal area construction can be satisfied in case of a flat interface [23]. In (11) the parameter T plays the role of temperature. The coexistence curve and the measurement data of the surface tension for this potential function can be found in [25].

For the second component the potential is chosen to be simply the density, i.e. $\psi^{(2)} = \rho^{(2)}$, so the second component is an ideal gas.

Finally the interaction force is calculated as the gradient of the pseudopotential, which in the lattice Boltzmann framework can be approximated as

$$F_\alpha^\sigma = -\psi^\sigma(x)\sum_{\bar\sigma}G_{\sigma\bar\sigma}\sum_i w_i\psi^{\bar\sigma}(x + c_i)c_i, \tag{12}$$

where $G_{\sigma\bar\sigma}$ is a Green function and it controls the strength of the interactions between the components σ and $\bar\sigma$.

For the computations presented in this work our single phase lattice Boltzmann code used for turbulent rod bundle flow simulations was extended for two-components. Just like for single phase flow, the rod bundle is modeled by periodically coupling the subchannels to each other both in the lateral and axial directions. The pitch to diameter ratio of a subchannel is $P/D = 1.34$ (see Figs. 1 and 2) which value corresponds to the parameters of a fuel assembly of a VVER 440 nuclear power plant. To make the calculations fast, domain decomposition was applied in the axial directions and the computations were run in a Linux PC cluster. Walls were modeled by the interpolated bounce–back method of Yu et al. [24]. We use lattice dimensions (lattice spacing and timestep) for all dimensional quantities throughout the paper. The parameters of the interparticle potential were chosen to be $T = 13$ and $C_1 = 0.01$. The critical temperature for this model is given by $T \approx 14.6$ (see [25] for the coexistence curve and other details). The parameters, which control the interactions between the components were $G_{12} = G_{21} = 0.01$. The relaxation parameters of the components τ^σ were unity for both components.

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