Simulation of bubbles motion side by side in lifting pipe of two-stage bubbles pump

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Abstract. Bubble pump was proposed to replace the traditional mechanical solution pump in the lithium bromide absorption chiller, for its advantageous feature that can be driven by industrial waste heat or solar energy or other low-grade energy. In two-stage bubble pump lithium bromide absorption refrigeration system, different flow patterns in lifting pipe have large relations with the performance of bubble pump. In this paper, a numerical simulation was performed to investigate the interaction of bubbles rising side by side in lithium bromide solution using the lattice Boltzmann method. The rising of bubbles with different configurations, including horizontal alignment and oblique alignment, was simulated. The results show that: the rising process of two side by side bubbles with horizontal alignment has two stages: close to the first, and then separated. The rising speed decreased with two bubbles close and increased with bubbles separate. For two different size rising bubbles with horizontal configuration, the bigger one has an attractive force on the little one, and the velocity of bigger bubble is much larger than the little one too.

1. Introduction
Bubble-bubble interaction is frequently encountered and will cause remarkable changes in the flow fields. Not only the shape, velocity and the track of bubble are affected by the bubble interaction, but also coalescence or breakup can take place via bubble collisions, consequently leading to a crucial impact on the hydrodynamics and the mass and heat transfer between gas-liquid phases. Many scholars have studied the behaviors of bubbles. Luz Amaya-Bower and Taehun Lee simulate the movement of bubble and analyse the characteristics of bubble motion by Lattice–Boltzmann method. Wijngaarden explore the change of resistance and lift force between bubbles under the condition of two bubbles or many bubbles with different arrangement, analysis the law of bubble motion such as deformation, attraction and rejection, meanwhile the bubble characteristic parameters are considered. Wang et al combines the HRIM algorithm and gas-liquid two-phase flow continuity equation to study the process of two coaxial bubbles fusion and finds that bubbles fusion time are related to the surface tension and viscosity of the liquid. Sun et al simulated many bubbles motion with large density ratio applying the three-dimensional free energy model, the results show that the initial position and size of bubbles have much influence on the rising bubbles shapes and surrounding flow. Jiang based on the OpenFOAM Open source code built three dimension numerical model of gas liquid two phase flow that can describe the bubble motion and simulated the rising process of single bubble and many side by side bubbles with different size in the calm water. The results show that putting new bubbles around the single within a certain range, the influence of original bubble flow field structure will increase with the new bubble size. He et al simulated a single bubble rising by buoyancy in viscous liquids with the level set method and numerical studied the effect of initial bubble
shape on the bubble dynamics and explained the influencing mechanism in detail. Legender [7] theoretical analyse the acting force between two level side by side bubbles and found that in terms of drag and lift coefficients, both the Reynolds number Re and the distance between bubbles S have great influence on it, and the change tendency is just opposite with the potential flow. In the aspects of many bubbles motion, Tryggvason [8-11] have done a lot of deeply research and have made some progress.

The above simulations indicated that bubble size and bubbles setting with different configurations have the decisive influence on bubble motion. There are not many researches about the process of side by side bubbles motion, especially in Lithium Bromide solution to vapour system with large density ratio. In this paper, boundary conditions and initial conditions are set corresponding to the actual experimental conditions and the physical properties of different systems, the motion characteristics of bubbles can be get.

2. Numerical Method
In this paper, a lattice Boltzmann method for simulating bubbles motion in liquid with large liquid-gas density ratio are proposed, in which extends Inamuro’s et al.’s [12] multiphase method n the present modeling, the velocity vectors of D3Q15 model are applied, and two particle velocity distribution functions, $f_i$ and $g_i$, are derived and expressed in equations (1) and (2), respectively. Where the function $f_i$ is used for calculating the order parameter which distinguishes two phases, and the function $g_i$ is for calculating the predicted velocity of two-phase fluid without a pressure gradient.

$$ f_i(x + c_i \Delta x, x + \Delta t) = f_i(x, t) + (1 - q)[f_i(x + c_i \Delta x, t) - f_i(x, t)] - \frac{1}{\tau_f}[f_i(x, t) - f_i^+(x, t)] $$

$$ g_i(x + c_i \Delta x, x + \Delta t) = g_i(x, t) - \frac{1}{\tau_g}[f_i(x, t) - f_i^+(x, t)] + 3E_i c_{ia} \frac{1}{\rho} \left( \frac{\partial}{\partial x_\alpha} \left( \frac{\partial u_\beta}{\partial x_\alpha} + \frac{\partial u_\alpha}{\partial x_\beta} \right) \right) \Delta x $$

$$ -3E_i c_{ic} (1 - (\rho_i / \rho)) g \Delta x $$

Functions $f_i^c$ and $g_i^c$ in Eq. (2) and Eq. (3) are given by

$$ f_i^c = H_i \phi + F_i[p_i - \kappa_f \phi \frac{\partial^2 \phi}{\partial x_\alpha^2} - \frac{\kappa_f}{6} \left( \frac{\partial \phi}{\partial x_\alpha} \right)^2] + 3E_i \phi c_{ia} u_a + E_i \kappa_i G_{ai}(\phi)c_{ia}c_{ia} $$

$$ g_i^c = E_i[1 + 3c_{ia}u_a - \frac{3}{2}u_\alpha u_\alpha + \frac{9}{2}c_{ia}c_{ia}u_\alpha u_\alpha + \frac{3}{2}(\tau_{g - \frac{1}{2}}) \Delta x \left( \frac{\partial u_\beta}{\partial x_\alpha} + \frac{\partial u_\alpha}{\partial x_\beta} \right)c_{ia}c_{ia}] $$

$$ + E_i \frac{\kappa_i}{\rho} G_{ai}(\rho)c_{ia}c_{ia} - \frac{2}{3} F_i \frac{\kappa_i}{\rho} \left( \frac{\partial \rho}{\partial x_\alpha} \right)^2 $$

The second order upwind is used to calculate the first order derivative, this format can get more accurate solution with strongly stability. Fourteen-point difference scheme is used for the second order derivative. Both the order parameter distinguishing two phases and the predicted velocity of the multiphase fluids are defined in terms of two particle velocity distribution functions as follows:

$$ \phi = \sum_{i=1}^{15} f_i $$

\[ u^* = \sum_{i=1}^{15} C_i g_i \]  

3. Numerical results and analysis

3.1. The validation of improved model

In the experiment of pump-free lithium bromide absorption refrigeration, the lifting pipe diameter of bubble pump is about 5-14 mm, the diameter of bubbles is about 1 mm in the bubble flow pattern. At temperature of 110°C, the density of 57.5% lithium bromide is about 1614.7 kg/m³, the density ratio of the liquid to the gas is of 2778, in the simulation, the physical properties of the gas and liquid has been considered, the viscosity ratio between to phase is 150, and the above lattice parameters are consistent with the experimental conditions. Back boundary is used on the surrounding and periodic boundary is used at the top and bottom of the cubic domain.

To verify the validity of the improved mode, the process of single bubble in lithium bromide solution (fig.1a) is simulated firstly, then comparing with the experiment result (fig.1b using high speed camera to shoot the process of single bubble in lithium bromide solution), the two motions and the changes of bubble shapes are similar, it reflect the accuracy and reliability of this model.

![Fig.1 comparison of simulation and experiment result of single bubble rising process](image)

3.2. Two bubbles with horizontal alignment

Setting two same size spherical bubbles which radius is 6 lattice steps length with horizontal alignment, and the distance between their centers is 16 lattice steps length. The process of bubbles rising as the fig.1 show: There are two stages in the rising process, the first stages(0-500 time steps), two bubbles rising side by side driven by the buoyancy and then the shape of them from spherical change to ellipsoid with relatively flat bottom surface. In this stage the interaction of two bubbles is attractive, the reason is that at the beginning of bubbles rising, the velocity is much small, the flow around bubbles is also week, each bubble have two swirls beside it, the two swirls in the middle of two bubbles offset each other, inertia plays a leading role, there will be generate a pressure gradient forward two bubbles center, so two bubbles will close to each other. Nevertheless the two bubbles not coalesce, after the 500 time steps, it is the second stage in the rising process, the interaction of two bubbles is repulsive. The velocity of bubble is increasing with the bubbles rising, the flow sounding the bubble is more intense, and due to the shape of bubbles have changes, the swirls beside each bubble are unbalance, resulting in a strong push-away effect on both ones.
Fig. 2 The shape and velocity vector distribution of two side by side bubbles

Fig. 3 shows the coordinates of two bubbles center, as two bubbles motion, the centers close to each other firstly, then to separate. From 100 time steps to 300 time steps, two bubbles close slowly, at the moment of 500 time step, the distance between two bubbles is shortest. Then two bubbles separate with an accelerated speed. In the rising process, two bubbles keep the relative level location, from fig.4, it can be reflected that: the rising speed decreased with two bubbles close and increased with bubbles separate.

3.3. Two bubbles with an oblique configuration
Setting two same size spherical bubbles which radius are 6 lattice steps length with an oblique configuration, the process of bubbles rising also has two stages as the fig.5 show: in first stage, inertia plays a leading role, both bubbles rise up and their shapes change, the lower bubble is pulled up by fluid flow induced by the wake behind the upper one, so the shape of lower bubble changed much serious. Each of bubble have two swirls beside the bottom, when they came close to a certain extent, two middle swirls integration, the interaction of two bubbles is repulsive. The upper part give a force to upper bubble rise towards right, and the lower part give a force to lower bubble rise towards left (as fig.6 shows), resulting in increase of the bubble distance.
3.4. Different size bubbles with center alignment

Setting a 6 radius small bubble and a 9 radius large bubble with center alignment, two bubbles rise up together, from 10 time steps to 700 time steps they close to each other firstly, then the distance between them became larger. Fig. 7 shows: in the rising process, both bubbles shape have changed, the small one have swing in the horizontal direction, and the final shape is ellipsoid, however the big one’s shape changing process is similar with single bubble, the final shape is ellipsoid cap. It is because in this condition, the small bubble has a small effect on large bubble rise, but the weak of large bubble have much influence to the small one, when they are closed, the small bubble in the upper position of the large bubble’s weak, there is a repulsive force to push it away, in the other hand, larger bubbles have bigger velocity, the large bubble rise more quickly, resulting the separation of two bubbles.
4. Conclusions
A lattice Boltzmann method for two-phase fluids with large density has been developed and applied to simulate side by side bubbles motion with different configurations. The following is concluded from the present study:

1) Two side by side bubbles with horizontal alignment rising process has two stages: Close to the first, and then separated. The rising speed decreased with two bubbles close and increased with bubbles separate.

2) Two bubbles with an oblique configuration, when they came close to a certain extent, two middle swirls integration, the interaction of two bubbles is repulsive, resulting in increase of the bubble distance.

3) Different size bubbles with center alignment, the weak of large bubble have much influence to the small one, the effect on small bubble of large bubble is attract or repulsive depend on the small bubble location in the weak of large bubble.

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