Numerische Simulationen von Blasenfluss und Verteilung der Blasengröße im Rohrkrümmer

Numerical simulations of bubble flow and size distribution in the Elbow

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Abstract

When studying the motion of foam, the foam is firstly generated by the static membrane technique in the vertical channel and passed through a 90° elbow into the horizontal channel. The experimental study often focused on the foam transportation in the horizontal region. In order to study the whole transportation procedure of the foam in the elbow, numerical simulation is investigated. We first simulated the bubble rising in the elbow and studied the velocity and the trace of the bubble. Furthermore, foam is initialized in the vertical channel and the whole transportation procedure in the elbow is simulated. Numerical results are first validated by comparing the bubble velocity and drag coefficient with the experimental results. Our numerical results reveal that the bubble velocity accelerates when rising into the elbow and then de-accelerates when approaching to the wall. The numerical results of the size distribution are also compared to the experimental data, which obeys a skewed distribution. Bubble coalescence as well as re-arrangement phenomena is shown in this region.

Introduction

Gas-liquid flow system are commonly encountered in the chemical, petrochemical, biochemical and metallurgical industries. The rising of bubbles in a viscous liquid due to buoyancy is one of typical phenomenon in gas-liquid systems, which is essential in various practical applications. For this reason, a comprehensive research of this multi-phase behavior has already been done. In lots of industrial applications, the foam is generated in the vertical channel, and then transports through an elbow and moves into the horizontal channel. This whole process is paid less attention in previous studies because there are some difficulties in both experimental and numerical studies, such as high costing experimental setting ups and high performance computing resources.

During the last decades, the technology of Computational Fluid Dynamics (CFD) is maturing at a rapid rate, which plays a more and more important role in analyzing and predicting the physical behavior. In order to describe the behavior of deformable bubbles, various methods have already been developed to predict the phase interface position and motions, such as Eulerian-Eulerian (E-E) method, Eulerian-Lagrangian (E-L) method and direct numerical simulation method (DNS). Among these three methods, DNS approach is often chosen, when accurate prediction of bubble motion is required. There are also various methods to predict the phase interface position and motion in DNS, such as Volume of Fluid method (VOF), Level Set method (LS) and Front Tracking method (Albadawi et al. 2013). The VOF method constitutes powerful and efficient technique for complex free surface problems. The advantage of the VOF method is that it guarantees mass conservation and obtains accurate results for substantial topology changes in interface without the requirement of re-initialization (van Sint Annaland et al. 2005), when comparing to the other methods and it is conceptually simple and easy extension to three dimensions. So it is adopted in the study of this paper.

In this paper, the whole process of bubble rising in an elbow is simulated and the change of velocity and drag coefficient is calculated. The first part of the research focuses on the bubble rising in the vertical channel of the elbow. The terminal velocity and constant drag coefficient are compared to the former experimental study. In the second part of the paper, a cluster of bubbles are initialized, numerical simulation of the bubble cluster transportation in the elbow is studied and compared to the experimental results.

Mathematical model and Physical analysis

Mathematical model

For the fluid dynamics, the continuity and momentum equation are fundamental equations. In this study, the fluid is the incompressible fluid, the continuity equation for incompressible Newtonian liquid can be described by the following equation:

$$\nabla \cdot \vec{u} = 0 \tag{1}$$

The momentum equation for the incompressible Newtonian liquid can be expressed by the following equation:

$$\frac{\partial(\rho\vec{u})}{\partial t} + \nabla \cdot (\rho\vec{u}\vec{u}) = -\nabla \mathrm{p} + \nabla \cdot \left(\mu(\nabla\vec{u} + (\nabla\vec{u})^T)\right) + F_s + \rho\vec{g} \tag{2}$$

For the surface tension force, the CSF(continuum surface force) model (Brackbill et al. 1992) is used. In the CSF model, the surface tension is assumed as constant along the surface and only the force normal to the interface is considered. In addition, the force at the interface is described as a volume force in the momentum equation. The force can be described by the following equation:

$$F_S = \sigma \frac{\rho\kappa\nabla\emptyset_f}{0.5(\rho_g + \rho_f)} \tag{3}$$

Where κ is the vector curvature, $\kappa = \nabla \cdot \hat{n}$, $\hat{n} = n/|n|$, $n = \nabla\emptyset_f$.

VOF method

The VOF (volume of fluid) defines the two fluids mixture through the volume fraction ∅ which the volume fraction is between 0 and 1, so it can satisfy the mass conservation extremely well and VOF method has higher accuracy (Chakraborty et al. 2009). The volume fraction is described by the following equation:

$$\begin{cases} \emptyset_f = 0 & \text{gas phase} \\ 0 < \emptyset_f < 1 & \text{interface} \\ \emptyset_f = 1 & \text{liquid phase} \end{cases} \tag{4}$$

In the VOF model, the phases are described through solving the volume fraction continuity equation. For the gas phase, it can be expressed by the following equation (Zhang et al. 2012):

$$\frac{\partial \emptyset_g}{\partial t} + (\vec{u} \cdot \nabla)\emptyset_g = 0 \quad (5)$$

The volume fraction of gas and liquid phases follows the equation below:

$$\emptyset_f + \emptyset_g = 1 \quad (6)$$

The calculation of density and viscosity of mixing fluid in a computational cell is shown by the following equation.

$$\rho(\vec{x}, t) = \emptyset_f(\vec{x}, t)\rho_f + [1 - \emptyset_f(\vec{x}, t)]\rho_g \quad (7)$$

$$\mu(\vec{x}, t) = \emptyset_f(\vec{x}, t)\mu_f + [1 - \emptyset_f(\vec{x}, t)]\mu_g \quad (8)$$

Drag analysis

In fluid dynamics, drag is a force acting opposite to the relative motion on the surface of the moving object respect to the surrounding fluid (Kurose et al. 2001). Drag coming primarily from differences in pressure and viscous shearing stresses depends on the properties of fluid and on the size, shape, and especially the velocity of the object. Usually drag can be expressed as:

$$\vec{F}_D = \frac{1}{2}\rho_f C_D A|\vec{u} - \vec{v}|(\vec{u} - \vec{v}) \quad (9)$$

Here $\vec{\mathrm{F}}_{\mathrm{D}}$ is the drag force, ρ_f is the density of the surrounding fluid, C_D is the drag coefficient, A is the projected surface area of the particle normal to the direction of its motion (Sabine et al. 2004), $\vec{u}$ the terminal velocity of the fluid and $\vec{\mathrm{v}}$ the velocity of the object. The terminal velocity is reached when the drag force is balanced with the buoyancy force. The term $\vec{u} - \vec{v}$ in Equation (9) indicates the relative velocity of the subject that is very important for the correlation of drag and lift coefficient. Therefore, it is defined as:

$$\vec{u}_{relative} = \vec{v} - \vec{u} \quad (10)$$

The drag coefficient is an important dimensionless number to evaluate the drag or resistance of an object in a fluid environment, of which the lower value usually indicates the object will have less aerodynamic or hydrodynamic drag. The drag coefficient is calculated based on the balance between buoyancy and drag, when the bubble rises in the fluid in the vertical direction with a constant terminal velocity. As is stated in Equation (11):

$$(\rho_f - \rho_b)gV_b = \frac{1}{2}\rho_f C_D A(v_z - u_z)^2 \quad (11)$$

Then the drag coefficient results in:

$$C_D = \frac{(\rho_f - \rho_b)gV_b}{\frac{1}{2}\rho_f A(v_z - u_z)^2} \quad (12)$$

Due to the incompressible property, the volume of the bubble can be directly calculated from Equation (12) with the spherical-equivalent diameter of bubble diameter (Wouter 2008).

$$V_b = \frac{1}{6}\pi d^3 \quad (13)$$

When a small bubble maintains the spherical shape, the projected area A can be defined:

$$A = \frac{1}{4}\pi d^2 \quad (14)$$

Combine the Equation (12), (13) and (14). The drag coefficient can be finally calculated as

$$C_D = \frac{4d(\rho_f - \rho_b)g}{3\rho_f(v_z - u_z)^2} \quad (15)$$

When bubbles rise in the quiscient liquid, the bubble terminal rising velocity can be also obtained by available terminal velocity models evaluated directly or by solving Equation (11) when drag coefficient is known.

$$V_T = \sqrt{\frac{4d(\rho_f - \rho_b)g}{3\rho_f C_D}} \tag{16}$$

Results and Discussion

In this section, the drag force acting on a single bubble moving in an elbow is studied. Previous research focused on the drag force on bubbles rising in a vertical column in quiescent liquid. This study extends the previous work, and studies the whole bubble movement from the vertical column to bend channel and finally in the horizontal channel. This section includes numerical validation and mesh study, velocity and drag force study.

Geometry and mesh generation of the Elbow

The geometry details of the elbow is shown in Fig.1. The elbow contains three parts: vertical channel, elbow and horizontal channel, which are separated by dashed line. Bubbles are positioned at the bottom of the elbow, near the inlet, and then start to rise in the elbow until touching the wall or flowing out of the outlet. The bottom part is vertical channel, which actually is a square duct with the size $8D * 16D$. Because the geometry changes with the diameter of bubble D.

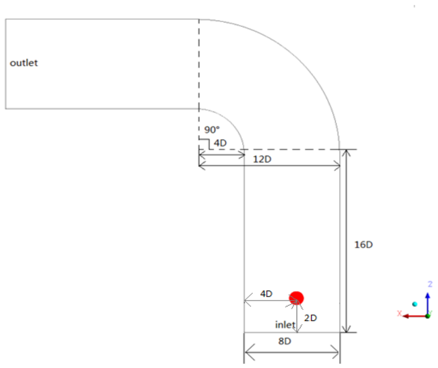

Fig. 1: Geometric model of elbow channel

The bubble with diameter D is centered at $(4D, 2D)$ filled with the gas phase and the rest domain of the elbow is filled with liquid. As is shown in Fig.1, the bottom of the vertical channel is set as velocity-inlet and the left boundary in the horizontal channel is set as outflow. Non-slip wall condition is set for the inner and the outer bended wall of the elbow. In order to resolve the shape of the elbow as well as the vertical and horizontal channel, blocked grid is generated by using ANSYS ICEM®, and the resolution per bubble diameter is kept the same as the mesh study.

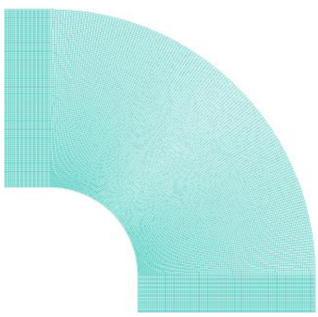

Fig. 2: Mesh generation of the elbow

Simulation of Single Bubble Rising in the Elbow

Bubble with 5mm diameter rises in quiescent is taken as an example and the velocity component in three directions are shown in Fig.3.

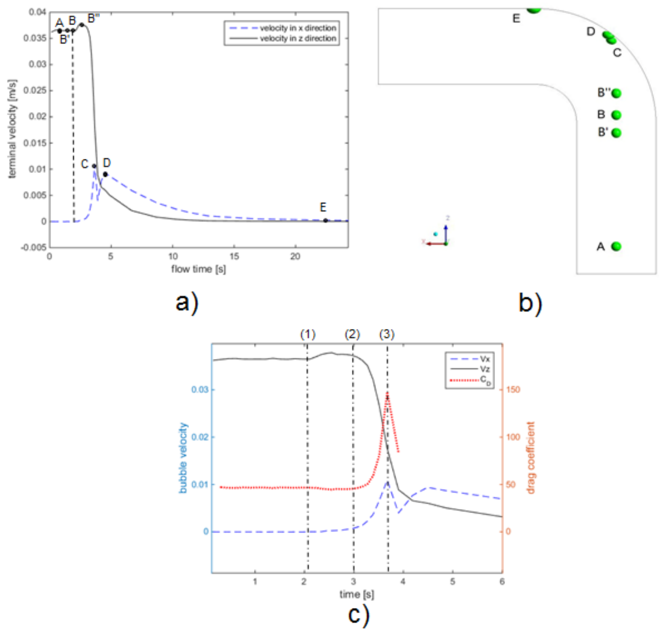

Fig. 3: Velocity of 5mm bubble with 0m/s liquid velocity; a) Bubble rising velocity in all directions; b) Bubble position in the elbow; c) Drag coefficient of the bubble in the elbow

As is seen in Fig.3a, the whole process of the bubble rising in an elbow can be divided into several sections with the marked points A, B, C, D and E. The points B′ and B″ represent the state of the bubble before and after point B, respectively. The bubble positions at these points are shown in Fig.3b. When the time before point A, the velocity in z direction increases up to the terminal velocity. In the section from point A to point B, the velocity in all the directions maintains as a constant value and it means that the bubble rises in the vertical channel with the terminal velocity and the drag force in the vertical direction balances the buoyancy force. Since there is no displacement in the other two directions, the velocity in x- and y-direction is zero. Once the velocity V_x starts to increase, it means that the bubble is ready to flow into the elbow part.

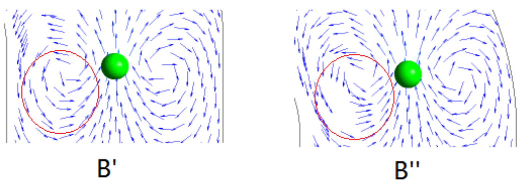

Fig. 4: Velocity vector of the liquid around the bubble at point B′ and B″

From point B to point C, the velocity V_z also increases a little because of the increasing pushing force of the liquid resulting from the change of the geometry. As is seen in Fig.4, when the bubble flows from point B′ to point B″, the geometry changes and it leads to a denser velocity vector field marked with red circle in the vicinity of the bubble, which indicates an extra pushing force acting on the bubble from the liquid.

Fig.3c shows the drag coefficient C_D when the bubble rises inside the elbow. One can observe that C_D doesn't change when the bubble moves in the vertical channel after reaching the terminal velocity. Afterwards, when the bubble flows into the elbow (shown between line (1) and (2)), the drag coefficient decreases a little because the vertical velocity increases. Between line (2) and (3), the drag coefficient raises up quickly because the bubble approaches to the top wall. The increasing trend of the drag coefficient results from the decrease of the bubble velocity. Finally, after line (3), the bubble slides on the wall, and therefore, Equation (15) is invalid here for the calculation of C_D.

The process from point B to C indicates that the bubble still rises and gets closer to the top wall of the elbow. Thus, the velocity V_z decreases rapidly because of the resistance of the liquid near the top wall. As seen from point C to D a sudden change of V_x happens caused by the quick shift of the mass center of the bubble and it denotes the procedure that the bubble reaches the wall and the shape changes from sphere to the hemisphere. From point C to point E the bubble continues to move along the wall and it is deaccelerated by the friction between the bubble and the wall until it finally sticks to the wall (point E).

Simulation of Foam Transportation in the Elbow

According to the experimental study, when the foam is generated and transported through an elbow, one of the prominent experimental results related to effect of the bending on the foam flow consists in the rearrangements of the bubbles with respect to their size. From the experimental results, rearrangement related secondary flows occurs because the gradient of the centrifugal forces prevailing in the flow bending reorder the bubbles with respect to the local densities. Consequently, large bubbles move to region of smaller radii while smaller bubbles tend to migrate to the radially outer region of the blending geometry.

Results of foam transportation inside elbow with uniform diameter is shown in Fig.5. In total 320 bubbles with 1mm diameter are initialized in the vertical channel of the elbow. After the bubble cluster transports through the elbow, different sizes of the bubbles can be observed. Similar to the experimental observation, the bubble with bigger diameter is mainly placed closed to the smaller radii, while the bubble with smaller diameter is migrated to the outer region of the elbow. Fig.6 shows the size distribution of the bubble, from the statistical point of view, the diameter of the bubble cluster obeys the skewed distribution with the highest percentage about 70%, which is also observed experimentally (Zoheidi et al. 2017).

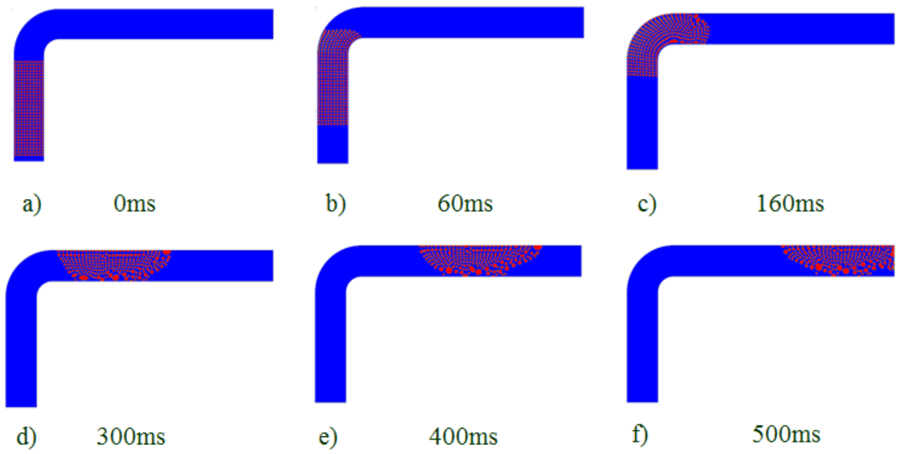

Fig. 5: Foam transportation in the elbow with uniform size as initial condition

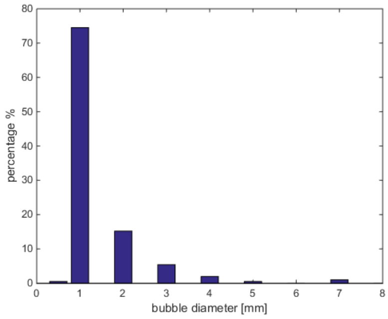

Fig. 6: Size distribution of the Foam in the horizontal channel

Fig.7 shows the bubble cluster transportation with different sizes initialized in the vertical channel. One can see that small bubbles turns to move to the outer side of the elbow, and coalescence to the others. On the other hand, the bigger bubbles turns to move to the small radii of the elbow. After the elbow section, the re-arrangement of the bubble finished, and the bubble cluster moves in the horizontal channel and is mainly influences by the liquid velocity as well as the buoyancy.

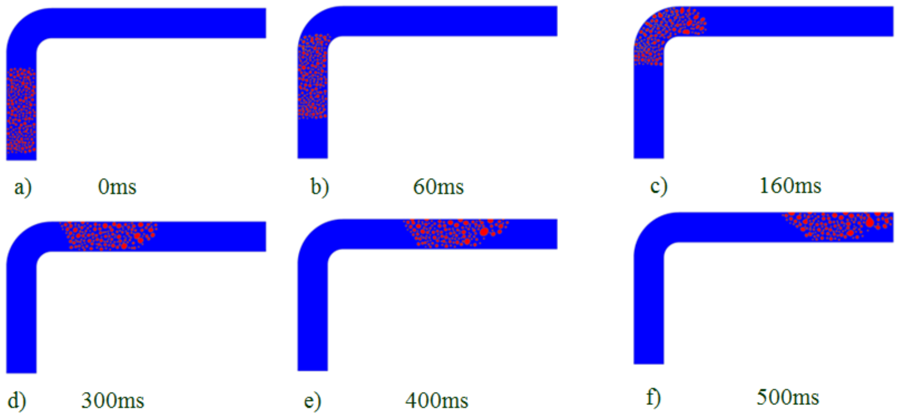

Fig. 7: Foam transportation with different sizes as initial condition

Conclusion

When the bubble rising in the elbow, the drag coefficient C_D can be divided into three parts that are the constant value, slow decreases, and sharp increases: in the vertical channel, the drag coefficient is constant; when the bubble flows into the elbow channel it starts to change: firstly decreases and then rises until it is very close to the wall.

The numerical results of the bubble cluster transportation is also shown. Compare to the experimental results, the numerical results are found to be comparable to the experiments with respect to the location of the bubble as well as the size distribution. More accurate results can be further studied by having a finer resolution, and interaction force can be added further in order to study the phenomena when the bubbles are very closed to each other.

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