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Numerical simulation of free ascension and coaxial coalescence of air bubbles using the volume of fluid method (VOF)

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ABSTRACT

The dynamics of a single air bubble, the wake structure, the instantaneous liquid velocity field around it and the coaxial coalescence of two successive bubbles have been widely studied in this work by using the VOF method on the software platform of Fluent. It is observed that the bubble rising trajectory changes from one dimension to three dimensions by decreasing the viscosity of the liquid phase. The different behaviors of air bubbles introduce various instantaneous bubbles wake structures which strongly depend on their shape and on the physical properties of the liquid phase. Indeed, as the solution viscosity decreases, the bubbles' shape changes from non-deformed (ellipsoidal) to the deformed shape. In the case of bubbles chain, the wake of the leading bubble significantly affects the shape, trajectory and velocity of the trailing bubble, as well as the velocity field of the liquid phase surrounding it. For high orifice air velocities and due to the wake of the leading bubble, the trailing bubble accelerates and approaches to the leading bubble and finally coalescence phenomenon occurs. During this process, the shape of the leading bubble becomes oblate while the shape of the trailing bubble is stretched in a vertical direction. Thus, the coalescence time and position of two successive bubbles generally increase with increasing the surface tension of the liquid and reducing its viscosity.

1. Introduction

The dynamics of a gas bubble is determined by its size and shape, which are themselves influenced by several parameters such as the gas injection flow rate, the orifice size and the physical properties of the surrounding liquid (surface tension, density and viscosity), etc. After detachment, the rising of a gas bubble is responsible for the development of a thin liquid layer at the bubble surface. This layer of liquid is directed from the top of the bubble to the bottom, surrounding the bubble shape. Inside this liquid layer vorticity occurs (Ryskin and Leal [1]). This phenomenon causes the detachment of this streamline around the bubble and the appearance of a wake behind it. In addition, a pressure gradient is generated at the lower surface of the bubble. In fact, the rising motion of the bubble contributes to the rise of the liquid behind it due to the drag force and to the pressure gradient which is related to the gradient of density.

Numerous studies have shown that the wake behind the bubble has an important effect on its behavior. In fact, Batchelor [2] has shown that the shape of the bubble wake depends on the intensity of the drag force generated by the bubble motion. In addition, Ryskin and Leal [1] have shown that the size of the recirculation zone behind a bubble is strongly dependent on its size and shape. Blanco and Magnaudet [3] added that the recirculation zone appears from a critical value of the aspect ratio located around 1.65–1.66. Thus, an axisymmetric wake becomes unstable when, for large Reynolds numbers, the bubble aspect ratio exceeds this critical value. Then the wake develops two vortex tubes of streamwise vorticity which, in turn, induce a horizontal force applied on the bubble and causes the sideways motion that characterizes the trajectory instabilities (Zenit et al. [4]). In addition, Buwa et al. [5] have observed that the strong vortex generated by a large leading bubble influences the growth of the succeeding bubble. Several studies (Oritz–Villafuerte et al. [6], Hassan et al. [7], Yu et al. [8] and Chen et al. [9]) have shown that the behavior of a bubble in a chain is different from that of a single bubble. Thus, the trailing bubbles are influenced by the movement of the liquid induced by the leading bubbles and they can be sucked in their wakes. However, the distance between two successive bubbles gradually decreases. Therefore, the velocity of the trailing bubble continues to increase under the effect of the wake behind the leading bubble until coalescence. Thus, the wake effect of the lead-

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Nomenclature

Bo	Bond number
C_D	bubble drag coefficient
D_b	bubble diameter (m)
D_{or}	orifice diameter (m)
F_S	surface tension force (N/ m^3)
g	gravity acceleration (m/s^2)
k	local surface curvature
Mo	Morton number
$\hat{n}$	unit surface normal vector
N_c	courant number
P	pressure (Pa)
R_{or}	orifice radius
Re	Reynolds number
S	separation distance
S*	dimensionless separation distance (S/D_{or})
T	time (s)
T_f	bubble formation time (s)
U_b	bubble velocity (m/s)
U_0	orifice air velocity (m/s)
$\vec{u}$	velocity vector (m/s)
V_b	detached bubble volume
V_F	Fritz volume
V_T	bubble terminal velocity
We	Weber number
x,y	cartesian coordinate (m)

Greek letters

k	curvature of the interface
α	volume fraction (dimensionless)
μ	viscosity (Pa.s)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

g	gas phase
l	liquid phase
or	orifice

ing bubble is found to be a primary factor that leads to bubble interactions, and is greatly influenced by the liquid viscosity (Katz and Meneveau. [10]; Ruzicka. [11]). Chen et al. [9] studied numerically the liquid pressure field of coaxial coalescence between bubbles of 4 mm in diameter. They showed that, under the action of the wake, the reduction of the pressure field behind the leading bubble would cause the phenomenon of coalescence. Furthermore, the coaxial coalescence process between two in-line bubbles at low Reynolds numbers have two forms: coalescence without conjunction, which could be divided into a contact stage and a drainage stage, and coalescence with conjunction which had an extra conjunction stage (Feng et al. [12]).

Other studies have been conducted to determine the relationship between the shape and the velocity of the bubble and their influences on the velocity field of the surrounding liquid (De Vries et al. [13], Wu and Gharib [14] and Kracht and Finch [15]). These studies found that the spherical bubbles have the lowest ascension velocities compared to other shapes. In this sense, Liu et al. [16] showed that the small bubbles (of order 1 mm) in water have a spherical shape and rise in a rectilinear trajectory with low velocities. By increasing their size, the bubbles are deformed to have an ellipsoidal, flattened ellipsoid, spherical cap or completely deformed shape and they move in a zigzag or helical trajectory with high oscillation velocities.

Concerning the effect of liquid phase properties, Anwar et al. [17] have shown that surface tension contributes to the conservation of the spherical shape of bubbles, and with the decrease of surface tension force bubble deformations begin. Liu and Zheng [18] showed by using PIV measurements that when the viscosity of the liquid decreases, the bubbles shape change from an ellipsoidal shape to a deformed one and their trajectories change from a rectilinear trajectory to a spiral one. In addition, Mikaelian et al. [19] have found that the viscosity and surface tension forces are responsible for the conservation of the bubbles shape whereas the inertial force is responsible for the oscillations of their interfaces. These authors added that the effect of viscosity and surface tension forces are predominant for low injection flow rates. While, for high injection flow rates, the viscosity and the surface tension forces are dominated by the inertial force.

In order to gain a complete understanding of the influence of the rising bubbles shape and trajectory on the characterization of the liquid phase flow structure around them, the bubble motion and the liquid phase flow structure in the wake of bubbles which are rising in rectilinear, zigzagging or spiraling path are studied by using the Volume of Fluid Method (VOF) method. In a first step, we are especially interested on the part of the liquid in the vicinity of the nozzle to observe the liquid flow structure in the rear of rising bubbles. In a second step, we studied the influence of the liquid flow structure around two successive bubbles on the bubble-bubble interaction and on the phenomenon of coalescence between them.

2. Numerical study

2.1. The VOF method

The VOF method has the advantages of easy realization, small computational complexity and high precision, and traces the volume of fluid in the grid, not the motion of fluid particles. The VOF method is applied to capture the interface (Hirt and Nichols [20]), the volume fraction α_k of each phase k in a computational cell is tracked throughout the domain, which means the fraction of the filled fluid volume in the grid to achieve the goal. If $\alpha_k = 1$, this indicates that the cell is filled with the phase k, $\alpha_k = 0$ this indicates that the cell does not contain the phase k. For $0 < \alpha_k < 1$, the cell contains the interface between the two phases. The sum of each volume fraction is equal to 1. The interface capture is based on the resolution of the volume fraction field, and then the reconstruction of the interface for the kth phase, the continuity equation is:

$$\nabla . u = 0 \tag{1}$$

A single momentum equation is solved throughout the domain, and the resulting velocity field is shared between the phases. The momentum equation for incompressible Newtonian fluid can be written as follows:

$$\frac{\partial}{\partial t}(\rho\vec{u}) + \nabla.(\rho\vec{u}\vec{u}) = -\nabla P + \nabla.\left\{\mu[\nabla\vec{u} + (\nabla\vec{u})^T]\right\} + \rho\vec{g} + F_S \tag{2}$$

In this equation F_s represents the surface tension force per unit volume which is considered by applying the continuum surface force (CSF) model proposed by Brackbill et al. [21]. In this model the surface tension force at the gas liquid interface is expressed as a volume force which is given by

$$F_s = \sigma \frac{\rho k \nabla \alpha_l}{0.5(\rho_l + \rho_g)} \tag{3}$$

$$\text{With} \quad k = \nabla.\hat{n}, \quad \hat{n} = n/|n|, \quad n = \nabla\alpha_k \tag{4}$$

Where σ is the coefficient of surface tension, $\hat{n}$ is the unit surface normal vector which is estimated from the gradient of the volume fraction and k is the local surface curvature. The subscripts l and g stand for the liquid and the gas phase, respectively.