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Numerical investigation of 3D bubble growth and detachment

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A R T I C L E I N F O

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A B S T R A C T

Combined with new numerical techniques, the boundary element method is adopted to study the 3D bubble growth and detachment from a submerged nozzle under constant pressure conditions in this paper. During the bubble growth, an efficient mesh topology optimization technique is adopted to eliminate ill-shaped elements for large deformation problems. At the bubble detachment, a 3D bubble pinching algorithm is employed to deal with the topological changes automatically. In this study, the cases with or without liquid cross flow are simulated numerically and the mechanism of bubble dynamic behaviors is analyzed. 3D results without cross flow show good agreement with the experimental and axisymmetric results in the literature, which validates the 3D numerical model. Besides, with the existence of the cross flow, the effects of cross flow velocity and nozzle radius on the bubble detachment characteristics are studied. The simulation results show that the bubble frequency and shape at the detachment can be controlled by exerting different cross flow velocities.

1. Introduction

Bubbling from orifices is a basic phenomenon of gas-liquid two-phase flow. It has wide applications, especially in ocean engineering, chemistry and energy fields, such as friction reduction of ships (Kodama et al., 2000; Moriguchi and Kato, 2002), air bubble breakwater (Zhang et al., 2010), wastewater treatment (Painmanakul et al., 2004), direct methanol fuel cell (Lu and Wang, 2004) and so on. Previous researchers have carried out plentiful study in this area, and the mechanism of the bubble growth and detachment from orifices has been revealed gradually.

When the gas is pumped through the immersed nozzle, the bubble forms at the tip of the nozzle. With the gas injection, a neck appears at the final stage of the bubble growth. When the liquid rushes into the neck, the bubble pinches off and it's split into two parts. The remaining part continues growing into a new bubble due to the gas pumping, while the detached part rises under the action of buoyancy. At a low gas flow rate, a single bubble will form, detach and rise periodically. In this paper, the focus is on the single bubble growth regime under constant pressure supply conditions.

Many researchers have studied the bubble formation from orifices in experimental and theoretical ways. Under the quiescent liquid condition, bubble formation experiments were carried out with different material and regime parameters (Jamialahmadi et al., 2001; Badam et al., 2007; Bolaños-Jiménez et al., 2008; Das et al., 2011; Bari and Robinson, 2013). Besides, Zhang and Tan (2003) and Loubière et al. (2004) conducted experiments under the condition of cross flow. The theoretical investigation is on the basis of force balance model. The bubble is assumed to be spherical through the expansion and detachment stages (Arebi and Dempster, 2008; Zhang and Shoji, 2001). By analyzing the quasi-static forces applied on the bubble, the position and volume of bubble can be obtained. However, many processes are simplified or ignored to make the problem solvable theoretically, which leads to the fact that the theoretical research only can predict the bubbling process qualitatively.

With the improvement of the computational fluid dynamics, many numerical methods have been applied to simulate bubble formation. Volume-of-fluid (VOF) method has successfully computed the bubble formation dynamics, as by Bari and Robinson (2013), Xu et al. (2013), Georgoulas et al. (2015) and Islam et al. (2015). The coupled level-set and volume-of-fluid method (CLSVOF) has also been employed in simulating bubble formation (Gerlach et al., 2006, 2007; Chakraborty et al., 2009; Sunder and Tomar, 2013). Das and Das (2009b) (2012) used Lagrangian-smoothed particle hydrodynamics (SPH) method to simulate the development of bubbles at a submerged orifice. Zhang et al. (2015b) and Zhang et al. (2017) applied the SPH method to simulate the dynamics of 3D bubbles. Although VOF, CLSVOF and SPH method can simulate the process of bubble formation, all of them occupy too much time regarding the 3D simulation. The high computational efficiency of the boundary element method (BEM) is an indispensable advantage over other methods. The dimensionality of the problem's geometry is reduced by one in BEM. Consequently, BEM becomes one of the most widely used methods in bubble dynamics (Zhang et al., 1993; Choi and Chahine, 2007; Choi et al., 2009;

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Chahine, 2014; Liu et al., 2014; Chahine et al., 2015; Li et al., 2015, 2016; Huang et al., 2016). Many researchers, such as Hooper (1986), Oguz and Prosperetti (1993), Oguz and Zeng (1997), Xiao and Tan (2005), Higuera and Medina (2006) and Gordillo et al. (2007), have adopted the boundary element method (BEM) to study the axisymmetric bubble formation. However, to the best knowledge of the authors, there are few papers discussing the ability of BEM in the simulation of 3D bubble formation. Only Oguz and Zeng (1997) simulated the 3D bubble formation before the detachment. Two numerical difficulties need to be solved. Firstly, during the bubble growth, the bubble mesh are stretched and become ill-shaped, which causes the calculation to break down. Secondly, when the bubble pinches off, the topology of mesh is changed. Unlike the mesh-free method (i.e. SPH) or the capturing interface method (i.e. VOF and CLSVOF), in which the topological relationship can be automatically handled, the BEM has to deal with the three dimensional mesh. This is a great challenge.

Optimization on the mesh topology is necessary when the deformation of the bubble is large. Zhang et al. (2001) employed the Adaptive Mesh Refinement to improve the topology of the toroidal bubble. Wang et al. (2003) proposed the elastic mesh technique (EMT) to ensure the uniform bubble mesh distribution. Zhang and Liu (2015) adopted the density potential method (DPM) and the edge swapping algorithm to optimize the 3D surface mesh during the bubble deformation. However, the bubble surface deforms enormously, and lots of ill-shaped elements are gathered together in our study. By merely adopting the above techniques, the quality of the bubble mesh will not be greatly improved.

The pinch-off of the bubble is a common phenomenon in the bubble dynamics. Oguz and Prosperetti (1993) used the BEM to investigate the pinch-off of an axisymmetric bubble. Zhang et al. (2015a) used the BEM to study the splitting of an axisymmetric toroidal bubble near a rigid boundary. However, using the BEM to study the pinch-off of the 3D bubble has been rarely studied. In view of above problems, a mesh topology optimization technique and a 3D bubble pinching algorithm are adopted to ensure the robust and efficient calculation in this work.

The numerical investigations on the bubble formation mainly focus on the effect of three aspects, including the fluid properties (Gerlach et al., 2007; Xu et al., 2013; Georgoulas et al., 2015; Islam et al., 2015), the regime and design parameters (Gerlach et al., 2005, 2007; Chakraborty et al., 2009; Bari and Robinson, 2013; Chen et al., 2013; Xu et al., 2013; Georgoulas et al., 2015; Islam et al., 2015; Simmons et al., 2015) and the gravity levels (Chakraborty et al., 2009; Georgoulas et al., 2015), on the dynamic characteristics of bubbles. Nevertheless, the effect of cross flow has not yet been systematically studied. On the basis of the 3D BEM model, the effect of cross flow is discussed in this paper.

Combined with new numerical techniques, BEM is adopted to study the 3D bubble growth and detachment from a submerged nozzle in the present work. The outline of this paper is as follows. Initially, the formulation of the problem is introduced in Section 2. Then, some numerical techniques of treating the mesh topology are described in detail in Section 3. In Section 3.1, on the basis of mesh subdivision, edge collapse procedure and Density Potential Method, a mesh topology optimization technique is adopted to ensure high mesh equality. A 3D bubble pinching algorithm is presented in Section 3.2. The convergence study about the mesh size is conducted in Section 3.3. In Section 4, the 3D model is validated by comparing the results with the experimental data and the axisymmetric results of Oguz and Prosperetti (1993). And the formation of bubble with cross flow is simulated. The mechanism of bubble dynamic behaviors is analyzed, and the effects of cross flow velocity and nozzle radius on the bubble detachment characteristics are discussed. Finally, Section 5 gives some conclusions drawn from this study.

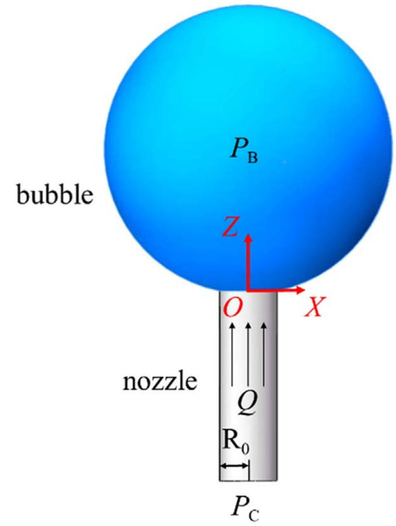

Fig. 1. Configuration of bubble formation from a nozzle.

2. Problem formulation

Bubbling from the immersed nozzle mainly consists of two stages, growing and detachment. A Cartesian coordinate system *O-XYZ* is built at the center of the orifice and the *Z* axis points in the opposite direction to gravity, as shown in Fig. 1. The bubble surface and nozzle surface constitute the closed boundary. The nozzle is connected to a pressurized chamber, and the chamber pressure P_C is always constant in this study.

The flow field is assumed to be incompressible, and the viscosity of the liquid is assumed to be comparable with that of water. It can be neglected (Oguz and Prosperetti, 1993; Oguz and Zeng, 1997; Xiao and Tan, 2005). Under the assumption of the irrotational fluid, the velocity potential ϕ satisfies Laplace's equation. The governing equation is

$$\nabla^2\phi = 0. \quad (1)$$

In the case of cross flow, the total velocity potential ϕ of the flow field can be decomposed into the flow incident potential ϕ_c and the disturbance potential ϕ_d induced by the bubble and nozzle. Therefore, ϕ can be expressed as

$$\phi = \phi_c + \phi_d = U_L X + \phi_d, \quad (2)$$

where U_L is the velocity of steady uniform flow, and ϕ_d can be calculated by the boundary integral method.

With the Green's equation, we can get

$$c(\boldsymbol{p})\phi_d(\boldsymbol{p}) = \iint_S \left(\frac{\partial\phi_d(\boldsymbol{q})}{\partial n}G(\boldsymbol{p},\boldsymbol{q}) - \phi_d(\boldsymbol{q})\frac{\partial G(\boldsymbol{p},\boldsymbol{q})}{\partial n}\right)dS, \quad (3)$$

where $\boldsymbol{p}$ is a vector pointing to a control point situated on the boundary S, $\boldsymbol{q}$ is a vector pointing to an integration point, and $\boldsymbol{n}$ is the unit normal vector pointing to the flow field. $\partial/\partial n$ is the normal derivative from the boundary. $c(\boldsymbol{p})$ is the solid angle of point $\boldsymbol{p}$. The Green function $G(\boldsymbol{p},\boldsymbol{q}) = |p-q|^{-1}$. S is the closed surface of the flow field, which consists of the bubble surface and nozzle surface.

The position vector $\boldsymbol{r}$ of the point on the bubble surface can be updated with the kinematic boundary condition

$$\frac{d\boldsymbol{r}}{dt} = \nabla\phi, \quad (4)$$

and

$$\nabla\phi = \nabla(\phi_c + \phi_d) = \nabla(U_L X + \phi_d). \quad (5)$$

The nozzle surface is rigidly fixed. The boundary condition is