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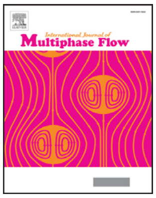

Toroidal bubble dynamics near a solid wall at different Reynolds number

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ABSTRACT

The bubble dynamics in a viscous liquid have significant applications, but the influence of viscosity on bubble dynamics near a solid wall are still not fully understood, especially for the toroidal bubble. In this paper, a numerical method is presented to study toroidal bubble dynamics near a solid wall in the viscous liquid. The liquid phase is assumed to be incompressible and separated from the gas by a free surface. Based on the finite volume method, the incompressible and viscous Navier–Stokes equations are discretized on the staggered grids, which are solved using the explicit projection method. A Lagrange multiplier method is used to deal with the additional constrain that the tangential stress equals zero, and the bubble surface is advected using a front tracking method. The numerical method is compared with the Rayleigh–Plesset solution for a single bubble with multi-oscillations, and the results between them are favorable with regard to bubble radius history. Finally, the toroidal bubble dynamics near a solid wall with different stand-off parameter ($\gamma = 1.5$, 0.95 and 0.6, respectively, where $\gamma = d/R_{max}$, d is the distance between the solid wall and the bubble center at the moment of formation and R_{max} is the maximum bubble radius) at different Reynolds number are studied, including water jet, peak pressure induced by water jet, water layer, bubble rupture, bubble migration, etc, where some important conclusions are obtained.

1. Introduction

Bubble motion in a viscous liquid is very interesting, and understanding of the bubble dynamics in the viscous liquid is of great significance in biological, medical and physical processes, including animal cells in bioreactors destroyed by the small bubbles (Boulton-Stone and Blake, 1993), and interaction of bubble with kidney stone and bony tissue subjected to a lithotripter shock wave (Calvisi et al., 2008; Iloreta et al., 2008; Wang, 2014). Cavitation bubble collapse near a structural surface is also a well-studied phenomenon in marine engineering. In the collapse stage, the cavitation bubble will radiate a high pressure outward and produce a high velocity water jet toward structural surface, which may cause serious damage to structures including ship propeller blades, hydraulic equipment, and turbomachinery (Blake and Gibson, 1987; Brennen, 2013; Plesset and Prosperetti, 1977; Song et al., 2017; Ye and Li, 2016). The mechanisms of interaction between bubbles and boundaries are associated with the viscosity of liquid, such as cavitation inception and separation (Zhang and Ni, 2014), so it is indispensable to study the cavitation bubble dynamics near a solid wall in the viscous liquid.

Many theoretical and experimental researches on cavitation bubble dynamics have been conducted. The liquid is commonly treated as inviscid, irrotational, and incompressible, so Rayleigh (1917) obtained the solution for cavitation bubbles in an infinite liquid by integrating the momentum equation. In order to study the influence of viscosity on the cavitation bubbles, Plesset and Prosperetti (1977) took viscosity as the dynamic boundary condition of bubble, and the solution obtained by this improved model was consistent with the data from experiments. In the experiments, laser-induced bubble and spark-generated bubble are customarily used to describe the dynamic behaviors of cavitation bubbles. Lauterborn and Bolle (1975) used the giant pulses of a *Q*-switched ruby laser to produce cavitation bubbles in distilled water, where the bubble dynamics in the vicinity of a solid boundary were studied by high-speed photography. Also, a lot of studies on the interaction of laser-induced bubbles with the solid wall were done by other researchers (Brujan et al., 2001; Shaw et al., 2001; Supponen et al., 2016; Tong et al., 1999; Vogel et al.,

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1989). The spark-generated bubbles, due to larger scale and produced easily, are extensively used to study the motion and deformation of cavitation bubbles. Tomita and Shima (1986) conducted a detailed experimental investigation on the collapse of a single spark-generated bubble near plastic material and the mechanism of impulsive pressure generation. Other researchers also completed a large amount of work on the spark-generated bubbles (Chahine et al., 1995; Gong et al., 2012; Gonzalez Avila et al., 2015; Krieger and Chahine, 2005; Lew et al., 2007). However, the experiments mainly focused on the interaction of bubble with the solid wall, and the influence of viscosity on the bubble dynamics were less described.

On the numerical side, various methodologies have been developed to describe the bubble motion. Due to convenience and high efficiency, the boundary element method (BEM) became the primary choice in bubble dynamics over last few decades (Best, 1993; Blake et al., 1986; Brujan et al., 2002; Liu et al., 2017b; Liu et al., 2017c; Wang, 2014; Wang et al., 1996; Zhang and Liu, 2015; Zhang et al., 2001). In BEM, the liquid is described in terms of a velocity potential based on the potential flow theory. In order to investigate the effect of viscosity on the bubble in potential flow, Miksis et al. (1982) assumed there was a very thin viscous boundary layer around the bubble, beyond which the liquid was still treated as potential flow. But they only included the normal viscous stress and the zero tangential stress condition was not satisfied. Boulton-Stone (1995) improved the boundary conditions so that the tangential stress condition at the boundary layer was taken into account. Joseph (2006) and Joseph and Wang (2004) used viscous pressure correction on the interface expressed by a harmonic series to compensate for the irrotational shear stress. Subsequently, On the basis of the work of previous scholars, the interaction between bubble and free surface with the viscous effect was also discussed by some researchers (Li and Ni, 2016; Lind and Phillips, 2013; Zhang and Ni, 2014). The other methodologies, including volume of fluid, and front tracking method, are the popular methods in recent years to study the bubble dynamics, where the Euler equation or Navier–Stokes equations are solved directly (Díaz-Damacillo et al., 2016; Hua et al., 2008; Koukouvinis et al., 2016a, 2016b; Liu et al., 2017a; Minsier et al., 2009; Popinet and Zaleski, 2002; Unverdi and Tryggvason, 1992; Yu et al., 1995). In the interface tracking or interface capturing approaches, the dynamics of rising bubbles was studied a lot considering the viscous effect (Díaz-Damacillo et al., 2016; Hua et al., 2008; Unverdi and Tryggvason, 1992), but there are few studies in cavitation bubbles that take into account the free-surface condition and the viscous effect. Yu et al. (1995) simulated the dynamics of cavitation bubble directly in the viscous shear flow by a finite difference combined with a front tracking method. Popinet and Zaleski (2002) proposed a lagrange multiplier method to deal with the zero tangential stress condition and systematically studied the effect of viscosity on formation of jets during collapse of cavitation bubbles near a rigid boundary using a front tracking method. Minsier et al. (2009) studied the effect of viscosity on the maximum jet front velocity with different stand-off parameter γ using the volume of fluid method. With neglect of liquid viscosity and based on the front tracking method (Popinet and Zaleski, 2002), Liu et al. (2017a) studied the bubble dynamics in the toroidal stage with stand-off parameter γ from 0.97 to 0.4.

For a spherical bubble, viscosity affects only the boundary condition (Plesset and Prosperetti, 1977), so it is appropriate that the boundary integral method uses a very thin boundary layer around the bubble to simulate the influence of viscosity on the bubble dynamics. But, for a non-spherical bubble, that the viscosity affects only the boundary condition is improper, and the influence of viscosity on the liquid beyond the bubble must be taken into consideration. Popinet and Zaleski (2002) directly solved the Navier–Stokes equations to simulate the influence of viscosity on jet formation and evolution of bubbles, mainly focusing on the study of a critical value of the Reynolds number below which jet cannot penetrate the bubble. The bubble dynamics in the toroidal stage were not studied in the work of Popinet and Zaleski (2002), so the influences of viscosity on the dynamic behaviors of toroidal bubble were not fully understood. In this paper, we directly solve the viscous and impressible Navier–Stokes equations combined with the front tracking method to research the influence of viscosity on the bubble dynamics, where the toroidal bubble dynamics near a solid wall with different stand-off parameter ($\gamma = 1.5$, 0.95 and 0.6, respectively) at different Reynolds number are studied, aiming at a deeper understanding of the dynamic characteristics of cavitation bubbles in the viscous liquid.

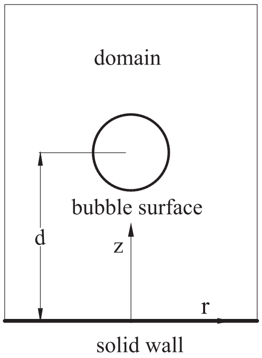

Fig. 1. Schematic diagram of bubble coordinates.

The rest of paper is organized as follows: Section 2 describes the numerical model, including governing equations for gas and liquid, non-dimensionalization, discrete governing equations, and advecting and redistributing the marker particles. Section 3 verifies the numerical model. In Section 4, mesh convergence, analysis of numerical results and numerical results compared with the critical Reynolds number are presented. In Section 5, the conclusions about the influence of viscosity on the bubble dynamics are presented.

2. Numerical model description

The code used in this paper is mainly based on the code of Popinet and Zaleski (2002) shared on http: //www.ida.upmc.fr/∼zaleski/codes/, except the treatment of the interface rupture that has been presented in Liu et al. (2017a). The main focus of this paper is to study the influence of viscosity on the toroidal bubble dynamics near a solid wall, including water jet, peak pressure induced by water jet, water layer, bubble rupture, bubble migration. The numerical model is repeated here for clarity.

2.1. Governing equations for gas and liquid

Bubble is a very common phenomenon in nature, which consists of gas and liquid. The bubble has an evident interface, and the gas and liquid is separated by the interface. Here we assume the fluid is adiabatic, where no mass and heat transfer across the interface. The liquid velocity induced by bubble is smaller than the speed of sound in the liquid, so the liquid is commonly assumed to be incompressible (Best, 1993; Wang et al., 1996). It is assumed that the liquid is undisturbed before bubble expansion and collapse, and the motion and deformation of bubble are thought to be axially symmetrical. Thus, this leads to a liquid system governed by the incompressible and viscous Navier–Stokes equations, as shown

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