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Numerical simulations and experimental validation on passive acoustic emissions during bubble formation

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ABSTRACT

In this paper, the volume of fluid (VOF) model in conjunction with continuum surface force (CSF) model is applied to numerically investigate the single bubble formation process in the bubble columns. Meanwhile, the hybrid method (large-eddy simulation (LES) and acoustic analogy method) is used for bubble acoustic prediction. Experimental results provide a reliable validation of the numerical results. Adaptive filtering technique and time–frequency analyses are adapted for the numerical acoustic data at the gas velocity of 0.1 m/s. The spectrum and spectrogram approaches indicate that the numerical acoustic data covers two principal frequency components, in which, one is the bubble generation rate and the other is the natural frequency of volumetric bubble oscillation. By combining the studies of flow field and acoustic signals, volumetric bubble oscillation is found to be excited by an axial water jet up into the bubble, immediately following the bubble detachment. The results of this study lead to the proposition that numerical simulation method could be applied to well understanding of the physics behind the passive acoustic emission.

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1. Introduction

Bubble exhausting from an underwater orifice consists of a number of complicated hydrodynamic processes, such as formation of submerged gas bubble, its subsequent growth, final departure and even its rising. This phenomenon is applied widely in a variety of chemical and process equipment, since bubble's generation and rise-up could stir up the liquid and intensify the interphase disturbance. The single bubble behavior plays an important role in determining the flow, mass and energy transfer characteristics in the bubble columns and fluidized beds [1–5]. Hence, the study on single bubble behavior is a vital issue and many experimental and theoretical investigations on the bubble formation from an orifice have been done in the past years [6–10].

In order to understand and measure mass transfer between the two phases, it is highly necessary to require the characteristics such as interfacial area, bubble size and type of flow regime etc. in the system. Existing techniques used to measure the above characteristics are generally not easy for on-line measurement nor intrusive to the process under investigation. Photography or video technique [11–14] requires transparent equipment and liquids, which is almost impractical for plant on-line measurement. Probe techniques [15] require direct contact with the gas phase to measure bubble size and gas hold-up in the system. Bubble sound has been investigated for charactering and monitoring bubble behavior in common gas-liquid systems of chemical engineering processes [16]. Recently it also has received a special focus in environment and marine sciences since methane trapped in permafrost is escaping from the sea bed within wide areas, and it has been an important accelerator of global warming [17–19].

The study of bubbles as underwater acoustic sources has drawn great attention [20–25], and bubble acoustics is well reviewed by Plesset and Prosperetii [26], and Leighton [27]. The gas exhausted from an underwater nozzle can produce bubbles which grow up and attach to the orifice. With the subsequent inflation, bubble connects with the orifice with a necking. Once buoyancy force exceeds the other applicable forces (surface tension, drag and pressure), the final necking fracture leads to a pulse of acoustic pressure in the flow field [28]. Generally, the classical bubble-acoustic Minnaert relation [21] is used to estimate the sound wave frequency with the bubble size,

$$f_a = \frac{1}{2\pi R}\sqrt{\frac{3\gamma P_a}{\rho}}, \tag{1}$$

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here f_a is the frequency in Hz, γ is the ratio of specific heats for gas, P_a is the absolute liquid pressure, R is the bubble equivalent spherical radius and ρ is the liquid density. This is the core of passive acoustic methodology, which has been widely and successfully used by many researchers [29–31] so as to obtain bubble sizes in diverse systems.

With the advancements in numerical technique and computing power over decades, the computational fluid dynamics (CFD) becomes a very effective means of studying the bubble behavior. Boundary integral method [32], the Lattice-Boltzmann method (LBM) [33] and the Larangian-smoothed particle hydrodynamics (SPH) method [34] have been performed to study the bubble formation dynamics. With respect to bubble acoustics, various numerical methods have been used, such as boundary element method (BEM) [35]. More recently, many numerical simulations apply simple but powerful VOF [36] model based on the concept of a fractional volume of fluid in order to treat the complicated gas-liquid interface in the geometry [37–39]. Compared with the experimental studies on bubble acoustics and the study on bubble formation dynamics, there are few attempts have been done on numerical investigations. Chen and Manasseh [40] established two-dimensional numerical model to simulate the development of air released from an underwater opening so as to obtain a good understanding of the acoustic signals. Hydrodynamic pressure fluctuations were monitored during the bubble formation process. However, bubble acoustic signatures were not fully demonstrated and explicitly analyzed. Manasseh et al. [41] reproduced the 0acoustic oscillation frequency of the bubble formation, but there uncertain factors for the shifted sequence of events in time domain still exist. Then Bui and Manasseh [42] studied the pressure fluctuations over the first few milliseconds during bubble detachment.

Although many numerical simulation studies on the bubbling dynamics in bubble columns have been done, the investigation on numerical prediction of bubble acoustic is obviously still needed, especially the fundamental understanding of the physics behind the acoustic emission. CFD methods play an indispensable role in the industrial design process, but for some reasons the use of CFD methods for hydro-acoustic prediction faces many difficulties [43]. One of the reasons is that the common Reynolds-averaged Navier-Stokes (RANS) method is to solve time-averaged equations, which are generally time-independent. Hydro-acoustic problems, however, are highly time-dependent by definition. The straightforward method for predicting hydro-acoustic is to solve the Navier-Stokes equations directly. This is regarded as direct numerical simulation (DNS). A huge computational cost is needed for this method solving all scales of a turbulent flow. Thus, the more suitable method for hydro-acoustic prediction may be the large eddy simulation (LES) technique.

In this paper, the finite volume method (FVM) has been used to simulate the bubble formation process and the VOF-CSF method is adopted to simulate three dimensional bubbles formed from the single orifice of small diameter (4 mm) at low gas velocity (0.1 m/s). In order to obtain the acoustic signals corresponding to the formation of single bubbles, the LES method in conjunction with FW-H equation are employed. With this method, the near-field hydrodynamics are computed to obtain velocity and pressure fluctuations that from the acoustic source terms for computation of the far-field acoustics. Air and water at atmospheric pressure and temperature are taken into account for the working fluids in the simulation. The experimental measurement of the air bubbles acoustics as they are formed in water is presented in Section 3. Eventually, effective signal processing via MATLAB Toolbox R2015 b are utilized for bubble acoustics.

2. Numerical methods

2.1. Governing equations

2.1.1. Continuity and momentum equations

The LES technique is adopted to compute the large-scale fluctuations, which are known as the most contributors to the noise generated in many problems. For an incompressible and constant density fluid, continuity and momentum equations are written as

$$\frac{\partial \widetilde{u_i}}{\partial x_i} = 0, \tag{2}$$

$$\frac{\partial \widetilde{u_i}}{\partial t} + \widetilde{u_j}\frac{\partial \widetilde{u_i}}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \tilde{p}}{\partial x_i} + \nu\frac{\partial^2 \widetilde{u_i}}{\partial x_i \partial x_j} + \frac{\partial \widetilde{\tau_{ij}}}{\partial x_j} + g_i + \overline{F_i^{ST}}, \tag{3}$$

where $\widetilde{u_i}$ is the filtered velocity component, $\tilde{p}$ is the filtered pressure, $\rho$is the fluid density, ν is the kinematic viscosity of the fluid, $\widetilde{\tau_{ij}}$ is the sub-grid stress in LES with the sub-grid scale model of wall-adapting local eddy-viscosity (WALE) model [44], g_i is the gravitational body force.

2.1.2. Volume of fluid (VOF) model

In the VOF model, a single set of momentum equations is shared by the fluids, and the volume fraction of each of the fluids is tracked throughout the domain. The VOF formulation relies on the fact that two or more fluids (or phases) are not interpenetrating [36]. A variable is introduced in the VOF model: the volume fraction of the phase in the computational cell φ. Its value may be 1 in the gas phase and 0 in the liquid phase if a gas-liquid system is involved. A value between 0 and 1 indicates an interface in the cell. In each control volume, the volume fraction of all phases sum to unity. In the medium with velocity field, the transport equation of fluid volume fraction is

$$\frac{\partial \varphi}{\partial t} + \mathrm{u}_i\frac{\partial \varphi}{\partial x_i} = 0, \tag{4}$$

Thus the variables and properties in any given cell are either purely representative of one of the phases, or representative of a mixture of the phases, depending upon the volume fraction values. In a gas-liquid two-phase system, the density and viscosity in each cell is given by

$$\rho = \varphi\rho_g + (1-\varphi)\rho_l, \tag{5}$$

$$\nu = \varphi\nu_g + (1-\varphi)\nu_l, \tag{6}$$

where the subscript g and l represent the gas phase and the liquid phase, respectively. The properties of gas and liquid phases in the simulations are shown in the following Table 1.

2.1.3. Continuum surface force (CSF) model

The CSF model [45] is adopted to deal with the surface tension in the interface, transforming the force at the surface into a volume force using the divergence theorem. It is this volume fore that is the source term, added to the momentum equation (2), written as

$$\overline{F_i^{ST}} = \frac{\sigma\kappa\nabla\varphi}{0.5(\rho_g+\rho_l)}, \tag{7}$$

where σ is the surface tension coefficient, κ is the interface curvature, $\kappa = \nabla\cdot\frac{\vec{n}}{|\vec{n}|}$, $\vec{n}$ is the surface normal which is defined as the gradient of φ.

2.1.4. Ffowcs Williams-Hawkings (FW-H) equation

The Ffowcs-Williams and Hawkings (FW-H) equation [46] is an extension of the classical Lighthill's acoustic analogy theory [47]. It

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