Three-dimensional numerical simulation of air exhausted from submerged nozzles

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Abstract. Underwater exhaust produces an intricate unsteady two-phase flow field. For exploring the methods to predict the structure of air-water flow field and revealing the interaction of gas and water, three-dimensional underwater gas jet model with the VOF multiphase flow tracking method was adopted to simulate the transient flow field of gas jet into water. The air-water two-phase flow and its acoustic characteristic of turbulent gas exhausted from underwater nozzles were experimentally investigated in the early stages. Process of bubbles formation, detachment, fragmentation and coalescence were recorded clearly. The simulated results which were compared with the prior experimental results proved that the model almost accurately catches the behaviour of underwater bubbles. A few points were set in the two phase flow field to monitor pressure fluctuation. It had shown that higher air flow rate causes intense gas-column contraction and consequent bubble fragmentation, leading to higher amplitude and frequency of pressure fluctuation.

1. Introduction
Air discharging through an underwater nozzle generates powerful acoustic pressure [1, 2], which has been identified as one of the main noise sources in submerged equipment. The behavior of the two-phase flow field underwater is also responsibility for the efficiency of many industrial proceedings such as chemical engineering, metallurgy industry and energy industry, etc.

Since 1917, Rayleigh [3] was amongst the first to study the problem in cavitation and bubble dynamics. Many researchers show their interest in the same question, for a review, see Plesset and Prosperetti [4] and Leighton [5]. Sound generated by bubbles has been investigated in quantity [6] but most of those studies focused on a single bubble. Based on the theory of volumetric oscillations of the bubble, the sound spectrum generated by the formation of a bubble at low to moderate bubbling rates can be calculated theoretically and has been used for bubble sizing [7]. However, with the increase of airflow rate, multiple bubbles are involved in the flow field, resulting in the irregular acoustic signal, and no simple theories can predict the sound field. The bubble dynamics are affected by many factors, such orifice size, gas flow rate, and induced by liquid flow. A two-dimensional model using the VOF method was built to simulate the bubble formation process, at airflow rates from 1m/s to 20m/s, by Chen and Manasseh [8]. Manasseh and Chen et al [9] also carried out a lot of experimental researches on acoustic characteristic from underwater exhaust. They studied the effects of different gas flow rate and different diameter of nozzles. Meanwhile, the underwater two-phase flow field was observed. Experimental results indicated that gas velocity and the sound pressure level existed nonlinear
relationship. Arghode et al [10] adopted five nozzles with different cross-sections to study the characteristics of submerged gas jet. The results showed that sound pressure level was affected by the orifice cross-section and pressure fluctuation was coupled with jet instabilities. At higher airflow rate, bubbling regime will transition to jetting regime. Zhao and Irons [11] applied combined Kelvin-Helmholtz and Rayleigh-Taylor instability analysis to obtain the critical velocity for jetting transitions. More recently, Shi Honghui [12], Chris Weiland [13] and Harby K. et al [14] investigated the flow structure of submerged high-speed gas jet experimentally. In numerical simulation of the complicated flows, Xu xiaoqiang [15] and Tang Jianing et al [16] successfully calculated the flow field with the VOF equations by two-dimensional model. The phenomena including expansion, bulge, necking and back-attack are highlighted in the jet process, which add the flow structure complexity. However, further studies are still necessary for the mechanism between sound generation and the flow structure of underwater exhaust.

In this paper, a 3D unsteady flow model was established to simulate air injected into opening quiescent water from nozzles which is located 760mm underwater with flow rates from 58m/s to 108m/s. The underwater two-phase flow fields were captured with RANS approaches and the VOF tracking method. Bubble formation, deformation, detachment, fragmentation and coalescence were simulated. The velocity and pressure fields caused by incompressible flow field fluctuation were analysis. The objective of this paper is to gain a good understanding of the relationship between the flow structure and the acoustic field.

2. Numerical methods
Consider air injected from a submerged nozzle into an open cylindrical container at room temperature. In this study, both air and water were assumed to be incompressible and immiscible. Bubbles were affected by inertial force, surface tension and buoyancy force, etc. Regardless of the phase transformation, there were obvious interfaces between air and water. The VOF (Volume of Fluid) methodology was used here to evolve and capture the interface.

2.1. Governing equations
The mean velocity \( \bar{u} \) and pressure \( \bar{p} \) of the underwater two-phase flow field could be described by the continuity and the Reynolds-averaged Navier-Stokes equations, which are written as:

\[
\frac{\partial \bar{u}_i}{\partial t} = 0
\]

\[
\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial (\bar{u}_i \bar{u}_j)}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ (\nu + \nu_{e}) \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \right] + g_i + \frac{1}{\rho} F_i^{SF}
\]

\[
\rho = \varphi \rho_g + (1-\varphi) \rho_l
\]

\[
\nu = \varphi \nu_g + (1-\varphi) \nu_l
\]

\[
F_i^{SF} = \sigma_k \frac{\nabla \varphi}{\phi} \cdot \mathbf{n} = \nabla \cdot \frac{\bar{n}}{\rho}
\]

Here, \( \nu \) is the kinematic viscosity; \( \nu_e \) is the eddy viscosity; \( g_i \) is the gravitational acceleration; \( \rho \) is the density of one fluid. \( \varphi \) is the volume fraction in the local cell of one fluid. Its value may be 0 when the cell is full of liquid phase and 1 when the cell is full of gas phase. A value between 0 and 1 indicates that the cell contains the interface between gas and liquid if a gas-liquid two-phase system is involved. The subscript \( g \) and \( l \) represent the gas phase and the liquid phase, respectively. The surface
tension $F_{ST}$, which is the last term of equation (2), modelled by the Continuum Surface tension Force (CSF) [17], could be computed via equation (5), where $\sigma$ is the surface tension coefficient; $\kappa$ is the interface curvature; $n$ is the surface normal which is defined as the gradient of $\phi$.

2.2. Initial and boundary conditions
In this paper, the initial liquid level height in the cylindrical container is 760mm, the remaining part is air phase which is opened to the atmosphere (see figure 1). Pressure-outlet where the gauge pressure is zero is adapted at the outlet. The inlet is defined as velocity-inlet, where the volume fraction of air phase is unity. The boundary conditions are $u=0$ at the walls.

2.3. Construction of numerical model
The simulation domain co-ordinates are [-200,200], [-200,200], [-60, 1000] mm in the x, y, z directions respectively. Gas ejection direction lies in the z positive direction, and the Cartesian co-ordinate origin at the central axis of the nozzle. The simulation model is used with a structural hexahedron grid of a total number of 700,000 cells. In order to provide good resolution of the two phase interface and the jet boundary layer, these relevant domains are refined to properly capture the air-water two-phase interface. Outside these domains, for reducing the computational cost, the size of mesh increases in proportion up to reach the boundary. The mesh structure of the 3D submerged gas exhaust model is shown in figure 2.

3. Results and discussions

3.1. Underwater two-phase flow field
Gas discharge through a submerged orifice into quiescent water is an unsteady process. The air-water two-phase flow field changes with the change of time and space. The initial stage of underwater two-phase flow fields with air injection at two different gas velocities of 58m/s and 108m/s are shown in figure 3. In the beginning, there is a gas-column formed with the effect of inertial force from injected air. Under the combined effect of surface tension, buoyancy and viscous shear force, an obvious “necking” phenomenon exists at the end of the gas-column away from nozzle, resulting in the first small bubble separated from the gas-column. Air continuous supplied from the upstream nozzle feed the gas-column becoming fatter and fatter. Meanwhile, the first bubble divided into lots of small bubbles downstream. In course of time, bubble formation and detachment occurred around the orifice periodically. After the bubble detached from the nozzle, the successor bubbles form. The subsequent bubbles may be absorbed into the dominant bubble and stretched by the dominant bubble (shown in figure 5).

As the gas injection velocity increased, the dominant forces are fluid inertia and buoyancy, instead of surface tension force [18]. It can be seen from figure 3 that the periodic time of bubbles formation becomes shorter with the increasing of underwater gas flow rate. Turbulent kinetic energy increase
brings more intense disturbance of the flow field. Under the strong disturbance, gas bubble could be more easily to break into lots of small bubbles. In the experimental video of underwater flow field, this phenomenon also exists in another form that there are more small bubbles in the flow field than lower gas injection velocity. In order to study the effect of bubble motion on flow field structure, bubble-bubble fragmentation and the resulting motion of the surrounding water under the influence are shown in figure 4. It can be found that the incoming gas puts the surrounding liquid in motion, and spiral movements exit around each bubble. Bubble-bubble fragmentation causes changes in direction of movement of partial flow field, and resulting in chaos in the surrounding flow field, which may just explain the reason of pressure fluctuation of the flow field around them. It is interesting to note that the surrounding liquid will enter into the large gas bubble when abrasion occurs.

![Figure 3. Initial stage of two-phase flow field with air injection velocity of 58m/s (top) and 108m/s (bottom).](image)

![Figure 4. Diagram of velocity vector and phase contour of 108m/s (X=0). Initial stage: 1.2ms, 1.4ms, 1.5ms, 1.6ms (from left to right, top). Successor bubbles: 40ms, 42ms, 44ms, 46ms (bottom).](image)

3.2. *Comparison with the experimental results of underwater two-phase flow field*

Either the experimental video or the simulated results had shown that the process of submerged bubbles generation is periodical. However, due to the complexity of the structure of flow field and the
intricacy of forces that bubbles taken, the form of submerged bubbles is not repeatable. Figure 5 displays the comparison of the underwater two-phase flow field between three-dimensional simulation and experiment results. It can be seen that the three-dimensional model which is used in this paper almost presents the underwater air-water flow field accurately.

Figure 5. Comparisons at 108m/s of gas injection velocity.

3.3. Pressure fluctuation and velocity fields
Five points (seen in figure 6) were set in the underwater two-phase flow field to monitor the variation of pressure. On account of the consistence of the pressure fluctuation trend, here, only data of point A with the gas flow rate of 108m/s is taken as an example to analyse.

Figure 6. Schematic diagram of pressure monitor points.

Figure 7. Pressure fluctuation at point A with gas velocity of 108m/s.
The history of hydrodynamic pressure with time at point A is demonstrated in Figure 7. It can be seen that the first bubble separated from the gas-column gives rise to a large pressure fluctuation. From the velocity vector diagram, it can be found that separation between the air bubbles causes vortex and reverse motion of the surrounding liquid, which should be responsibility for the pressure fluctuation during the time of 1.2ms to 1.6ms, 40ms to 44ms. Submerged bubble detached from the nozzle is also accompanied by a significant liquid pressure variation (see t=38ms to t=40ms in figure 5 and figure 7). These significant changes of the pressure could be the main contribution of the low frequency acoustic signal. As time progress, the air-water flow field becomes more complexity. When bubble detachment, fragmentation, collapse, coalescence and natural oscillation exited simultaneously, the pressure fluctuation presents irregular performance (see t=80ms to t=100ms in figure 5 and figure 7). Furthermore, with the increase of the gas flow rate, the peaks of pressure fluctuation are greater than those of lower gas flow rate.

4. Conclusions
Gas exhausted through an underwater nozzle into quiescent water with high gas flow rates have been successfully simulated in three-dimensional form. The simulation results show bubble-bubble fragmentation, interaction and coalescence, and bubble-nozzle detachment been supposed to from the early experimental observation. With the increase in air flow rate, the frequency of bubble detached from the submerged nozzle also increases. Moreover, the hydrodynamic pressure fluctuation in the air-water flow field was monitored. Bubble-bubble fragmentation and bubble-nozzle detachment both give rise to a significant pressure fluctuation, which should be the major contributor in the strong acoustic signatures. Simultaneously, the velocity vector fields were analysed to explain the phenomenon of pressure fluctuation. It is helpful to understand the formation and evolution of the submerged two-phase flow fields and pressure fields. This paper creates a foundation for further acoustic analysis.

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