PREDICTION OF BUBBLE GENERATION BASED ON ACOUSTIC EMISSION

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Abstract

The noise associated with gas discharged from a submerged nozzle is of great interest to many industries because of its important applications. For example, it can be used to size bubbles and to detect gas flow rate. However, the physics associated with the acoustic emission due to bubble formation is complex, particularly when a large number of bubbles are involved, and has not been fully understood. In this study, the dynamics of the bubble formation from a submerged nozzle has been studied experimentally using the Particle Droplet Image Analysis (PDIA) technique. An improved model for prediction of the bubble generation rate and size distribution based on acoustic emission is presented. The experimental study is carried out in a large water tank, of dimensions 10 m x 10 m x 6 m, using multiple hydrophones. The water tank is carefully calibrated in order to provide free-field measurements. The predicted bubble generation rate and size distribution have been compared with the experimental data. It has been found that the predicted results are in good agreement with the experimental measurement, implying that an accurate prediction of acoustic emission associated with a bubbling plume from a submerged nozzle can be achieved by using the model.

1. Introduction

Noise generated by bubbles is a complex phenomenon and has attracted intensive research for many years because of its importance to a range of applications, such as its contribution to ocean background noise, its use in medical diagnostic techniques and its significance to the stealth of naval platforms.

A comprehensive coverage of the fundamentals of bubble acoustics can be found in [1]. Examples of previous studies in this field include works by [2], [3], [4] and [5]. These studies have mainly focused on a single bubble and its resonance frequency, or bubble formation dynamics at a low discharge rate. The frequency of acoustic waves generated by the formation of a single bubble from a nozzle at low gas discharge rates can be theoretically calculated and has been widely used to size bubbles. However, the research activities on the modelling of the sound levels are restricted, and it becomes rarer when a turbulent gas discharge is involved. According to the recent researches by [1], [6] and [7] at a high gas discharge rate, the gas-water flow will exhibit a transition from bubbling to jetting. However, for gas discharging in deep water, the gas-water flow will have bubbling behaviour which is the focus of the current study [6].

Modelling and measurement of sound generated by a highly turbulent discharge water-gas flow (bubbling plume) can be very challenging. There is no simple theory that can be used to predict the associated acoustic field because of the complicated dynamics in the bubble formation process ([7], [9], and [10] . For example, the sound emission due to bubble fragmentation caused by turbulence may be different to that of a bubble excited by its detachment from a nozzle. At high gas discharge rates, the formation of bubbles can be strongly influenced by the nozzle size and the induced liquid flow. Many experimental and theoretical studies have been reported to explore in this area (e.g. [5], [10], [12], [13], [14] and [17]).

Leighton and White [17] developed a model for the noise generated by a bubbling plume emitted from a submerged nozzle. In that model they assumed that the bubbles of different sizes will be excited at a constant ratio to its equilibrium radius regardless of the gas discharge flow rates. They claimed that adopting such a simplification was mainly due to the lack of consistent experimental data. Our previous study [15] found that the initial excitation of bubbles during the formation process has a strong effect on the acoustic emission, and a constant initial excitation ratio is unable to adequately describe the bubble formation dynamics and to predict the associated acoustic emission.

The aim of this study is to develop an improved model for predicting bubble generation rate and size distribution based on the acoustic emission signature. The effects of the initial excitation condition on the bubble generation rate and size distribution are investigated. The influence of gas discharge rate and nozzle dimension on the acoustic emission signature and bubble generations are also studied. The predicted bubble size distributions are compared with the optical measurements using the PDIA technique. The ultimate goal of the study is to develop a model to predict acoustic emission based on the characteristics of a bubbling plume.

2. Theory

As mentioned above, one can find many practical applications of the resonance frequency produced by the formation of bubbles. Such applications do not necessarily require information on the magnitude of sound pressure induced by bubble oscillation, but require the frequency of acoustic waves emitted by the bubbles. Modelling the relationship between acoustic emission and bubble generation rate for high flow rates is more challenging because of the range of bubble sizes and interaction of bubbles in the bubbling plume. In addition, estimating the size distribution of bubbles in this flow requires an accurate measurement of the sound pressure. Leighton and White [17] provided a model to calculate the acoustic pressure radiated by a single bubble pulsating at resonance frequency ω_0 at time t and a distance r (far field)

$$P_b(t) \approx \mathrm{Re}\left\{ \rho_0 \frac{(\omega_0 R_0)^2}{r} R_{0\varepsilon i} e^{j\omega_0 (t-t_i)} e^{-\omega_0 \delta_{tot} (t-t_i)/2} \mathrm{H}(t\text{-}t_i) \right\} \quad (1)$$

R_0 is the initial bubble size, $R_{0\varepsilon i}$ is the initial displacement of the bubble's wall, ρ_0 is the density in the far field, H is the Heaviside step function, and t_i is retard time. The decay of the pressure induced by the oscillating bubble is determined by the dimensionless damping constant δ_{tot} defined by [7] as

$$\delta_{tot} = \delta_{th} + \delta_{vis} + \delta_{rad}. \quad (2)$$

The thermal damping constant δ_{th}, the viscous damping constant δ_{vis} and the radiation damping constant δ_{rad} are given by

$$\delta_{th} = 4.41 \times 10^{-4} \sqrt{\omega_0 / 2\pi}\ ;\ \delta_{vis} = \frac{4\mu}{\rho_0 \omega_0 R_0^2}\ ;\ \delta_{rad} = \frac{\omega_0 R_0}{c} \quad (3)$$

Here μ is dynamic viscosity of water and c is speed of sound in the far field. The squared magnitude of the Fourier transform of equation (1) yields

$$\left|P_{b1}(\omega, R_0)\right|^2 = \left[\omega_0^2 R_0^3 \frac{\rho_0}{\pi r}\frac{R_{0\varepsilon i}}{R_0}\right]^2 \times \left(\frac{4\left[(\omega_0\delta_{tot})^2 + 4\omega^2\right]}{\left[(\omega_0\delta_{tot})^2 + 4(\omega_0-\omega)^2\right]\left[(\omega_0\delta_{tot})^2 + 4(\omega_0+\omega)^2\right]}\right). \quad (4)$$

Considering a bubbling jet and assuming that the oscillation of each bubble is not correlated to the motion of surrounding bubbles, the monopole emissions of individual bubbles are then uncorrelated. If the bubble generation distribution $D(R_0)$ of the bubbling plume is specified (for example using the results from a computational fluid dynamics (CFD) simulation), the power spectral density $S(\omega)$ of far-field sound can be calculated by using

$$S(\omega) = \int_0^\infty D(R_0)\left|P_{b1}(\omega, R_0)\right|^2 dR_0 \quad (5)$$

The relationship between the initial bubble size R_0 and the resonance is given by [16]

$$\omega_0 = \frac{1}{R_0}\sqrt{\frac{3\gamma P_0}{\rho}} \quad (6)$$

in which P_0 is the static pressure and γ is the ratio of specific heats. To solve the model given by equations (4), (5), and (6), the ratio $R_{0\varepsilon i}/R_0$ of the initial displacement of a bubble to the equilibrium radius, has to be specified. This ratio will be referred as the initial excitation ratio. This parameter is difficult to model because it essentially depends on the bubble formation mechanism, such as fragmentation or coalescence. Modelling $R_{0\varepsilon i}/R_0$ will be discussed later.

To estimate the bubble generation rate using the measured acoustic emission, a bubble number spectrum or bubble generation rate spectrum is defined as

$$\psi(n) = \int_{R_{l,n}}^{R_{u,n}} D(R_0)dR_0 \quad (7)$$

Using this definition, equation (5) is approximated as

$$S(\omega_k) \approx \sum_{n=1}^{N_b}\psi(n)\left|P_{01}(\omega_k, R_n^c)\right|^2 \quad (8)$$

If the multiple bubbles are divided into N_b groups, the bubble number spectrum $\psi(n)$ is a single column vector of N_k elements. Eq. 8 forms a $(N_k \times N_b)$ spectral matrix, which will be square if the number of frequencies N_k is equal to the number of bubble groups N_b. In such a case, equation (8) can be solved by inverting the spectrum matrix to obtain the bubble number spectrum as a function of the initial bubble size R_0 and the power spectral density of the sound field. The total flow rate of the system, Q, can be then obtained by integrating the bubble number spectrum.

To apply the model, accurate acoustic emission signature of a bubbling jet has to be obtained. This is obtained in a big water tank.

3. Experimental Apparatus

Experiments were carried out in a tank with a dimension of 10 m × 10 m × 6 m. Regulated and filtered air was released into the tank through a nozzle. The air flow rate was measured with a flow meter and held constant for each experiment. Acoustic measurements were obtained by four randomly located RESON® Type 4013 hydrophones. Data was recorded and analysed using a 16-channel DEWETRON® analyser (see Figure 1 for a schematic). Experiments were carried out using three nozzle sizes and 9 gas discharge rates, as listed in Table 1. For each experiment, 30 seconds of data were recorded with a sampling frequency of 48 kHz.

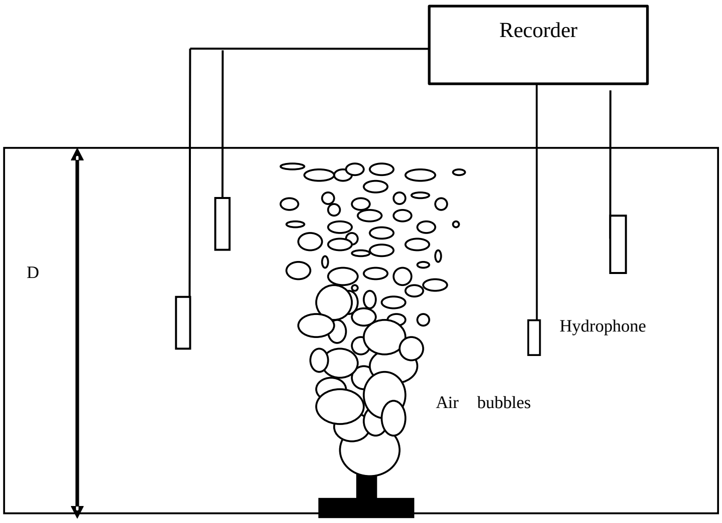


Figure 1. Schematic diagram of the experimental apparatus

Table 1. Experimental conditions

Nozzle diameter (mm)	Gas discharge rate (L/min)								
4.0	1	2.5	5	7.5	15	20	30	40	50
6.0	1	2.5	5	7.5	15	20	30	40	50
9.0	1	2.5	5	7.5	15	20	30	40	50

The bubble size distributions were determined using the Particle/Droplet Image Analyser (PDIA) technique in conjunction with a digital single-lens reflex (DSLR) camera. In the current study, a Nikon D4 DSLR camera was used to capture bubble images at a rate of one frame per second (fps) at a resolution of 2000 × 1327 pixels. A sequence of 400 digital images was captured over the duration of 400 second for each experimental condition. Moreover, with the aid of a Broncolor Scoro 3000e flash unit as the background lighting source, a short-exposure time of 1/8000 second was achieved to freeze the instantaneous motion of bubbles on each image. Therefore, the size and shape of each bubble can be visually and digitally obtained.

Figure 2 shows a typical instantaneous digital image of the bubbles extracted from a sequence of 400 images. With the aid of a Nikon 300 mm lens and a TC-20E tele converter in the current optical setting, each image provides a Field of View (FOV) of 105.7 mm x 70.2 mm, which covers part of the bubbling plume. A calibration target was introduced into the quiescent liquid to determine the pixel to real distance ratio on the focusing plane.

The PDIA software VisiSize was employed to determine the statistical bubble size distribution at each experimental condition. In practice, an imaging analysis technique called background subtraction was utilised to eliminate unwanted background noises and obstructs. Figure 3 illustrates the image analysis results of the bubble size distribution for a 9mm nozzle at a gas injection rate of 15 L/min. Within a duration of 400 second (400 images) the total of 34,983 bubbles were counted. Due to the limitations of image resolution as well as the field of view, the minimum measurable bubble diameter was 235 μm, while the maximum bubble diameter captured was approximately 71 mm. Moreover, the statistical number mean diameter was 608 μm and the Sauter mean was 748 μm respectively.

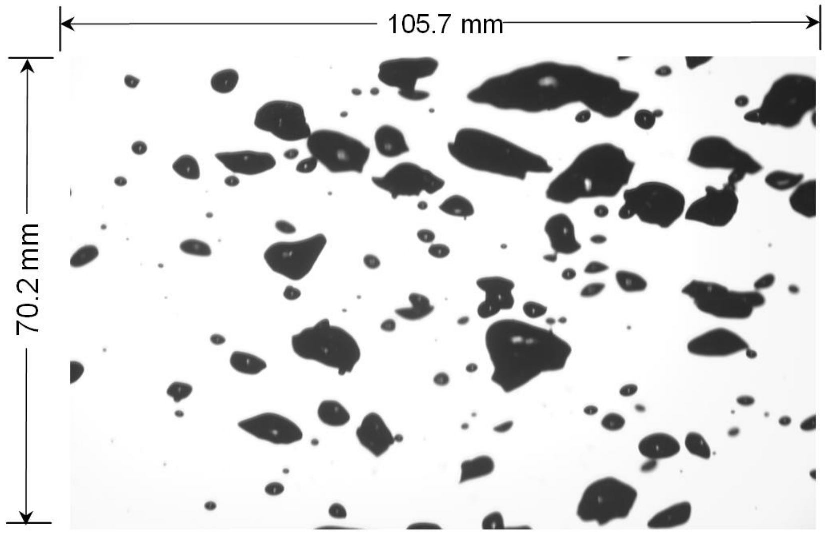


Figure 2. Typical instantaneous digital image of bubble distribution

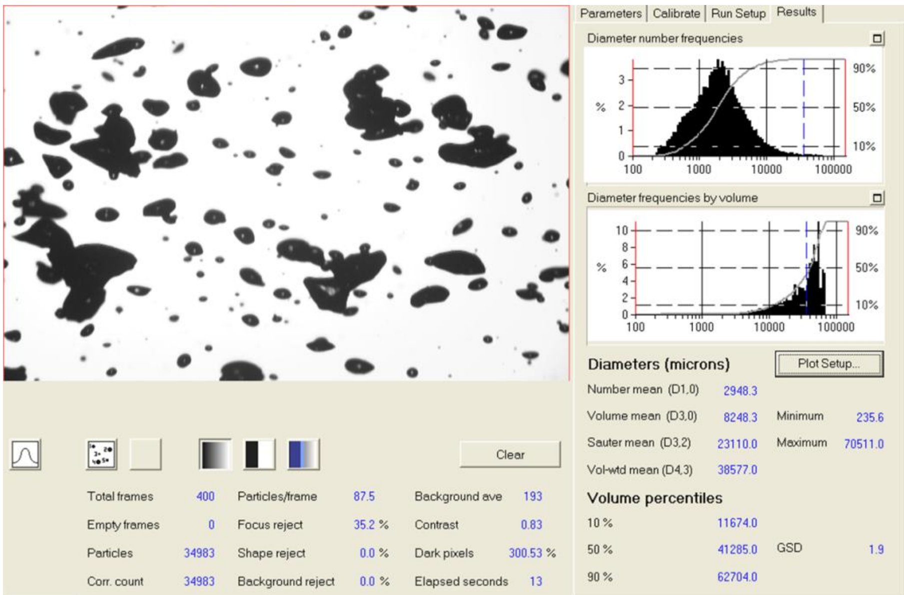


Figure 3. Bubble size distribution for 9 mm nozzle at gas discharge rate of 15 L/min

4. Results and Discussion

4.1 Acoustic emission

To predict the bubble generation rate and size distribution, accurate sound pressure is required. Because the water tank is a highly reverberant environment, the sound pressure level produced solely from the source is contaminated by the sound reflected from the tank boundaries; so the technique presented by [17] has been employed. This technique requires knowledge of the critical radius of the water thank based on reverberant measurement of the tank. The averaged sound pressure is obtained by randomly located four hydrophones, and it is then corrected to obtain the free-field sound pressure level at 1m away from the bubble source via a logarithmic manipulation based on the determined reverberation characteristics of the water tank.

The measured sound pressure levels LP in third octave bands at 1 m from the bubbling plume are shown in Figure 4 for the experiment using the 6 mm nozzle. The background noise level measured during quiescent condition is also included in the figure. It can be seen that the noise generated by the bubbles is at least 5 dB higher than the background noise in the frequency range of 800 to 16 kHz for all air flow rates. It can also be seen that the acoustic emission intensifies with an increase in air flow rate.

The effect of nozzle diameter on the acoustic emission is shown in Figure 5. Noise is increased between 3 to 8 kHz is observed for both 6 mm and 9 mm nozzle. The effect of the nozzle sizes on noise level is not very significant. This is consistent with other experiments on discharge gas flow in the bubbling region, which shows that the nozzle size has a limited effect on the noise [1].

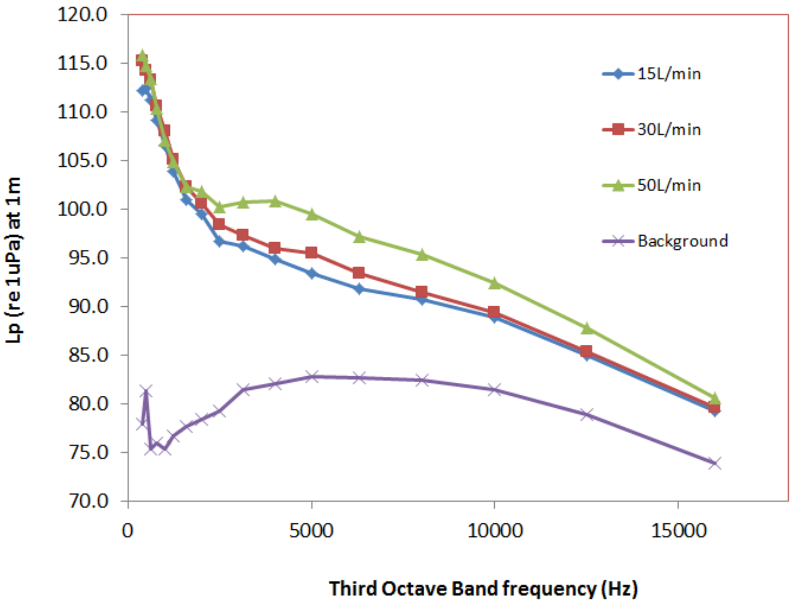


Figure 4. Sound pressure level re 1 μPa at 1m for the 6 mm nozzle in third octave band.

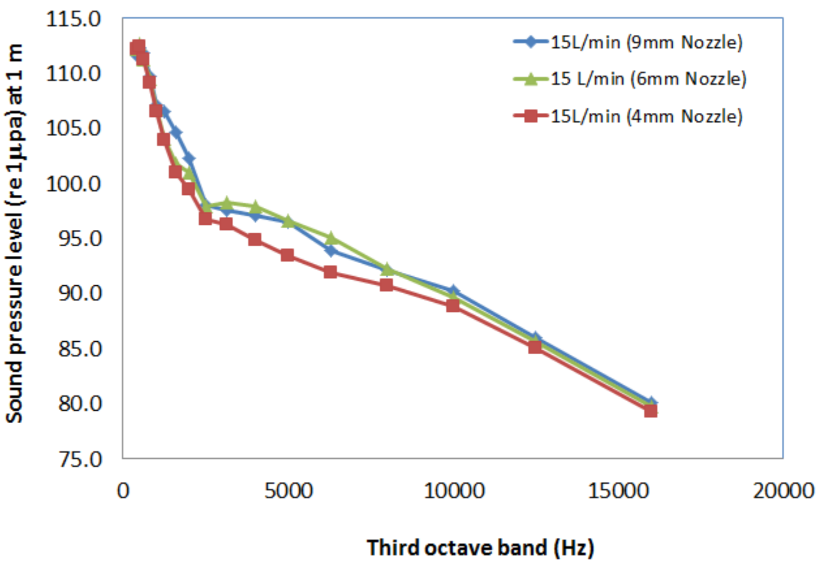


Figure 5. Effect of nozzle size on sound pressure level

4.2 Prediction of the bubble generation rate spectrum

Equations (2) to (8) are solved by MATLAB to obtain the bubble population spectrum based on the measured acoustic emission. In the model, the initial excitation ratio, $R_{0\varepsilon i}/R_0$ has to be specified. However, there are few reported data to support a particular value for this parameter. Reported values vary from $R_{0\varepsilon i}/R_0 \approx 1\times10^{-5}$ [3] to $R_{0\varepsilon i}/R_0 \approx 1.5x10^{-2}$ [18]. The limited available data show a thousand fold difference in the value of $R_{0\varepsilon i}/R_0$ for a given bubble radius. In principle, the value should not be a constant since the bubble formation process involves broader physics. For a gently releasing bubble, the surface tension determines the level of deviation of bubble radius from its equilibrium size when it detaches from a nozzle. However, for high discharge gas flow, the bubble break-up or coalescence would be enhanced due to the induced turbulent liquid flow. For those two scenarios, the dynamics of the latter would lead to a lower value of $R_{0\varepsilon i}/R_0$ compared with the former. To verify this hypothesis, a varying initial excitation ratio is introduced in the original model. The values of varying initial excitation ratios are assigned to have the best match to the measured flow rate, and are shown in Figure 6. It can be seen that the initial excitation ratios show a well behaved trend for all gas discharge flow rates and different nozzles, in which the ratio decreases exponentially with an increase in gas discharge flow rate. This indeed confirms the suggested hypothesis. Based on the predicted data, an empirical formula for the excitation ratio as a function of gas flow rate is derived as

$$R_{0i}/R_0 = \frac{0.023}{1-0.77e^{(-0.028Q)}} \tag{9}$$

This empirical formula has been applied to the 6 mm Nozzle, and the error of the predicted total gas discharge flow rates was found to be less than 15% (not shown here).

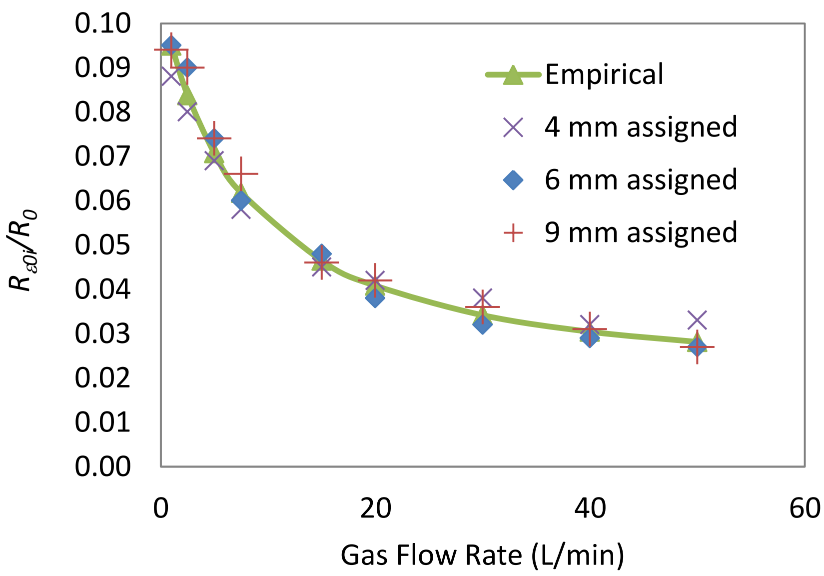
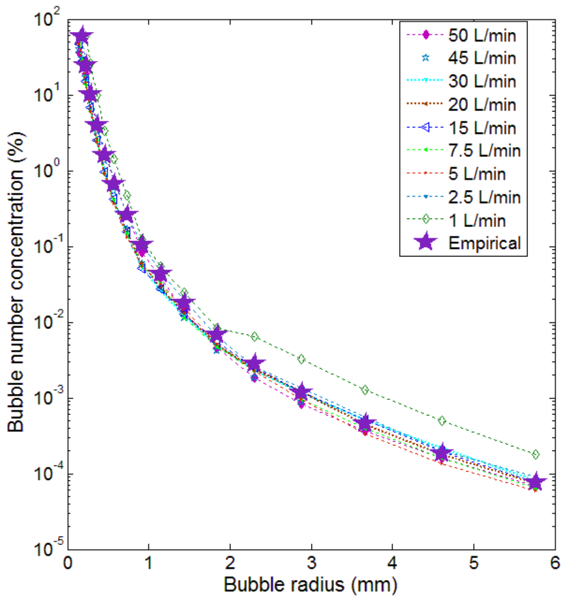
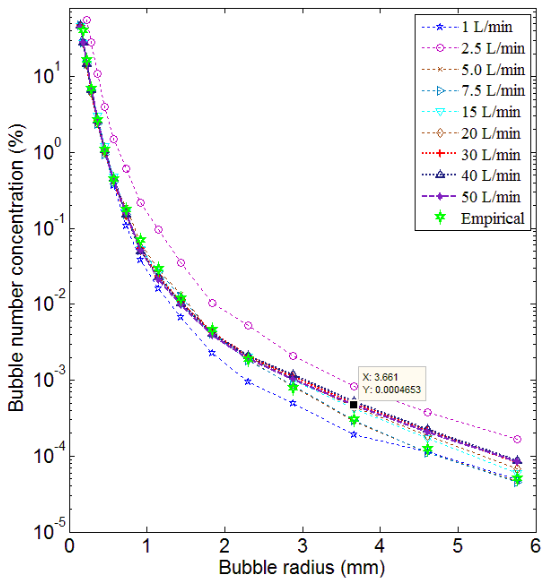


Figure 6. The assigned initial excitation ratio as function of gas discharge rate

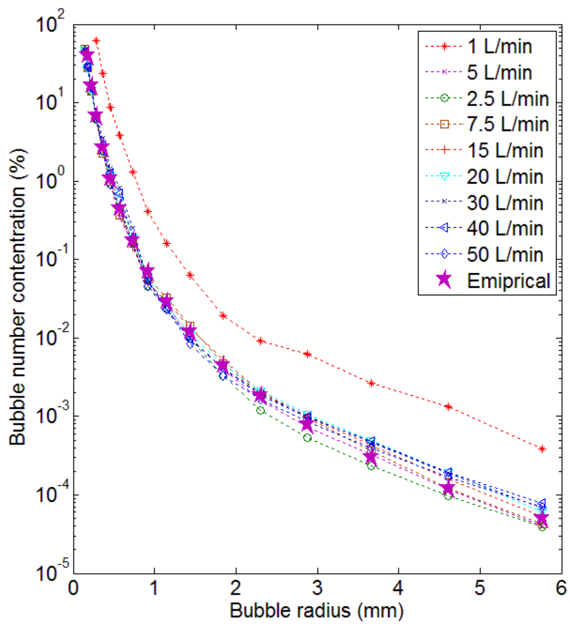
The predicted bubble number concentrations as a function of bubble radius, at different flow rates for 4 mm, 6 mm and 9 mm diameter nozzles, are shown in Figure 7. The bubble number concentration for different flow rates seem to collapse on top of each other signifying a similar trend except for a gas flow rate of 1 L/min. This is particularly the case for 4 mm nozzle (see Figure 7a). For 6 mm and 9 mm nozzles, a slight increase in bubble number concentration of larger bubbles is observed when the gas flow increases (Figures 7b and 7c). This indicates that the nozzle size has some influence on the formation of the large bubbles. The well-collapsed bubble number concentration spectrum for the 4 mm nozzle leads to an empirical formula. This derived formula is applied to the 6 mm and 9 mm nozzles and the results are also shown in Figure 7b and 7c respectively. It can be seen that the bubble number spectrums estimated by the empirical formula agree well with the predicted results in both cases. This implies that the acoustic emission is strongly related to the gas discharge rate and the effect of the nozzle dimension is secondary. The empirical formula for bubble number spectrum provides a useful tool for scaling the bubbling flow noise for engineering applications. For a given gas flow rate, the bubble number concentration spectra can be adopted to predict the bubble numbers distribution and the associated acoustic emission. To improve the empirical formula, a further study to include the nozzle dimension will be conducted although its effect is not strong.



(a) For 4 mm nozzle



(b) For 6 mm nozzle

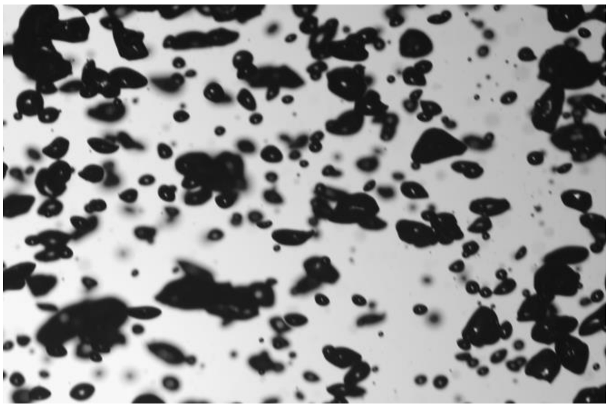


(c) For 9 mm nozzle

Figure 7. Predicted bubble number concentration spectrum for 4 mm, 6 mm and 9 mm nozzles at different gas discharge rates

4.3 Measurement of bubble size distribution

Two snap shots of the measured bubble size distribution for 4 mm and 9 mm nozzles at a flow rate of 30 L/min are shown in Figures 8a and Figure 8b. The processed data for 7.5 L/min and 30 L/min with the 6 mm nozzle are given in Figure 9. The measured bubble size distribution for two nozzle sizes supports the predicted trend, which shows the bubbling plume is mainly made of bubble of a radius less than 5mm. The characteristics of the bubbling plume are very similar for two nozzles in terms of bubble size distribution. The measured bubble number concentration spectrum is given in Figure 9. Note that the measured bubble size distribution presented in a 0.5 mm increment. It can be seen that the number of bubbles of radius larger than 5mm increases with an increase in flow rate, which agrees with the prediction. However, there is a discrepancy between the predicted (Figure 7b) and the measured bubble number concentration. It is believed that the discrepancy can be mainly attributes to two reason, firstly the restricted region scanned by the camera, means that the measured data is highly localised, and, secondly the limitation of the equipment. However, the measured bubble size distributions at different locations have demonstrated a significant increase in the number of bubbles of radius less than 2mm and steady decrease in the number of bubbles of a radius larger than 6 mm in the downstream of the bubbling plume. This would lead to a higher number concentration of small bubbles and low concentration of large bubbles. The improvement of the optical measurement will be the focus of our future work.



(a) For 4 mm nozzle

(b) For 9 mm nozzle

Figure 8. Sample image of bubble distribution at gas discharge rate of 30 L/min through 4 and 9 mm nozzles

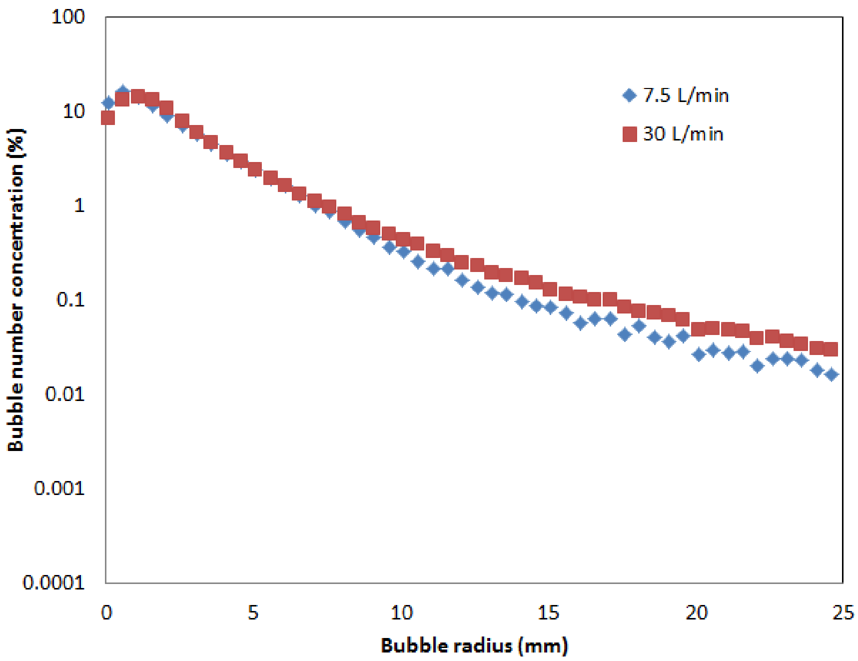


Figure 9. Measured bubble population spectrum for 7.5 L/min and 30 L/min for 6 mm nozzle

5. Conclusions

Exhaust gas from submerged nozzles of different diameter at different discharge rates is studied. The bubble formation process is acoustically investigated. It has been found that the noise generated by the exhaust gas is strongly related to the gas discharge rate. The size of nozzles has a secondary effect. It has been confirmed that the noise associated with bubbling plume is dependent upon the bubble formation process. At a high gas flow rate, bubble break-up is enhanced by the induced liquid flow and the initial deviation from the equilibrium state is small compared with a gentle bubble formation process. An empirical relationship between the ratio $R_{0\varepsilon i}/R_0$ of the initial displacement of a bubble to the equilibrium radius and gas discharge flow rate is given. An improved model is presented for predicting bubble size distribution based on the acoustic emissions. It has been found that the bubble number concentration spectrum can be scaled by gas flow rate for the flow region studied. This is an important and practically useful to many engineering applications. The predicted bubble number concentration is compared with experimental measurement. The predicted results agree with the experimental data in principle although a further improvement of the comparison is required.

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