Three stages of bubble formation on submerged orifice under constant gas flow rate

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Xianxian Yu, Yiwei Wang*, Chenguang Huang, Tezhuan Du

Key Laboratory for Mechanics in Fluid Solid Coupling Systems, Institute of
Mechanics, Chinese Academy of Sciences
Hai dian District No.15 Beisihuanxi Road, Beijing, China
*wangyw@imech.ac.cn

Abstract. Bubble formation is involved in many engineering applications. It is important to
understand the dynamics of bubble formation. This work reports experimental and numerical
results of bubble formation on submerged orifice under constant gas flow rate. Compressible
large eddy simulation combined volume of fluid (VOF) was adopted in simulation and results
was validated by experiment. Bubble formation is divided into three stages in this paper,
expansion stage, elongation stage and pinch-off stage. In expansion stage, The bubble grows
radially due the incoming gas flux, but the bubble base remains attached to the orifice. But
as gas injected, the spherical bubble will go into the elongation stage when the downward
resultant force is lager than upward resultant force. And when bubble neck's length is bigger
than $\sqrt{2}R_o$, the bubble will go into pinch-off stage. Cylindrical Rayleigh-Plesset equation can
be used to describe the pinch-off stage. Uncertain parameter r in it is given reference value in
this paper.

1. Introduction

The process of bubble formation at submerged orifice is very significant in many engineering
applications, such as bubble column, gas-liquid separator, cavitation, etc.
Owning to its practical importance, the phenomenon of bubble formation and pitch-off has been
widely studied theoretically and experimentally for decades.

Sufficient investigations of bubble formation at submerged orifice have been reported, as
described in articles of Zhang et al(1), Kumar et al(2-4). Different models have been proposed to study
the formation of bubble. In low gas flow rate, the formation of bubble is dominant by buoyancy and
surface tension, which can be described by Young-Laplace equation (5). Gerlach(5; 6) et al. did a
comprehensive study on bubble formation at a submerged orifice with low and medium constant gas
flow rate. They brought up a theoretical model of the quasi-static bubble formation at very small flow-
rate. It was observed that the strong vortex generated by a large leading bubble influences the growth
of the succeeding bubble and leads the period-1 bubbling regime to the period-2 bubbling regime. In
Zhang's work (1) the bubbling phenomena above a submerged orifice can be divided into four regimes,
single bubbling, pairing, double coalescence and triple bubble formation. The experimental results and
the theoretical prediction both demonstrate that bubble interaction is the primary reason for the
aperiodic characteristics of bubble departure. Pinch-off in liquid is a complex and key point in bubble
formation process which draws considerable interest(7, 8). Burton J C(8) used cylindrical version of
the general Rayleigh-Plesset equation and a 100000 frame-per-second video to analyze the pinch-off
of nitrogen gas bubbles in fluids with a wide range of viscosity. They found a power law solution in

time, neglecting the pressure in the bubble. If the external fluid is highly viscous ($\eta_{ext} > 100\,cP$), the bubble neck radius is proportional to the time before break, τ, and decreases smoothly to zero. If the external fluid has low viscosity ($\eta_{ext} < 10\,cP$), the radius scales as $\tau^{1/2}$.

There have been much evaluable theoretical and experimental results in this literature. In the present paper, we showed our numerical and experimental work on bubble formation with experiment and simulation, including analysis on three stages of formation process and discussion on Rayleigh-Plesset equation, etc. It is hoped make some new reference to this phenomenon.
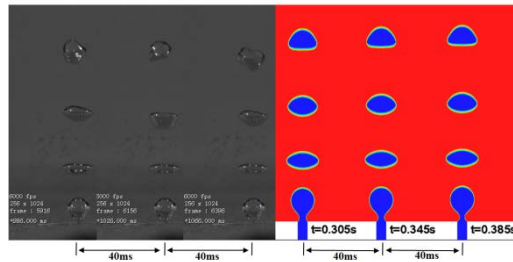
2. Experiment and simulation

Fig. 1 Experiment and simulation

Bubble formation is a two phase phenomenon. For the numerical treatment of this problem, compressible large eddy simulation (LES) combined with a volume of fluid (VOF) method is used in this paper. Experiment is taken in a small water tank and recorded by a high-speed camera. Fig.1 shows the results of experiment and simulation. The orifice radius is 1mm and gsa flow rate is 100ml/min.

3. Results and discussion

In present paper, bubble formation ware divided into three stages, as shown in Figure 2, including stage Ⅰ-bubble expansion, stage Ⅱ-bubble elongation and stageⅢ-bubble pinch-off. In stage Ⅰ, sphere bubble takes shape and grows bigger with continuous injected gas through the channel, as Figure 2-Ⅰ shows. When bubble becomes big enough, the bottom part begins to contract and a short cylindrical bubble appears , through which the whole bubble contacts with the orifice, as shown in Figure 2-Ⅱ. When stretched to a certain length, the cylindrical bubble will lose stability, contracting inwards until detaches from the orifice. This stage is called pinch-off, as shown in Figure2-Ⅲ. The detached bubble rises up in the water during the following time until reaches the water surface.
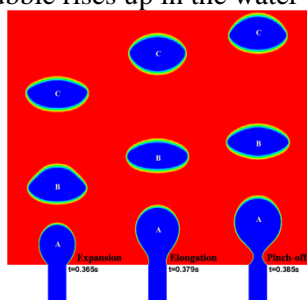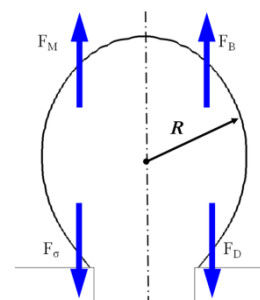

Fig. 2 Bubble formation in a single period

Fig. 3 Force analysis on bubble

Expansion stage. In expansion stage, as shown in Fig.3, the bubble grows radially due to the incoming gas flux, but the bubble base remains attached to the orifice. The growth rate of bubble volume nearly equals to the gas flow rate. As gas injected, the downward resultant force (surface tense F_σ and drag force F_D) becomes lager than upward resultant force (buoyancy F_B and gas momentum force F_M), ie $F_{B+}F_M \geq F_\sigma + F_D$, the spherical bubble goes into the elongation stage then.

Elongation stage. In elongation stage, the bubble rises away from the orifice, but still attached to it through a neck, which is thought to be a stable cylindrical bubble, represented by Figure 4. When the

cylindrical bubble lose its stability, the bubble will go into next stage. The stability criterion of the neck is studied here. The cylindrical bubble is assumed to get a very small disturbance and its surface tense changes, as shown in Figure 5. Surface tense can be sorted into $F_{\sigma-out}$ and $F_{\sigma-in}$. $F_{\sigma-out}$ could help the distortional neck to recover while $F_{\sigma-in}$ stops it. If $\Delta F_{\sigma-out} \geq \Delta F_{\sigma-in}$, the bubble can keep stable, or else it will lose stability. $\Delta F_{\sigma-out} = \dfrac{\sigma}{R_{out}}$, $\Delta F_{\sigma-in} = \dfrac{\sigma}{R_o - \Delta y} - \dfrac{\sigma}{R_o}$ where R_o is radius of the orifice, σ is surface tense coefficient and R_{out} is curvature radius corresponding to $F_{\sigma-out}$. $R_{out} = \dfrac{l^2 + \Delta y^2}{2\Delta y}$ where Δy is relatively small compared with l and Δy^2 can be neglected. Though analysis, we can get the stability criterion $l \leq \sqrt{2}R_o$ where R_o is radius of the orifice.
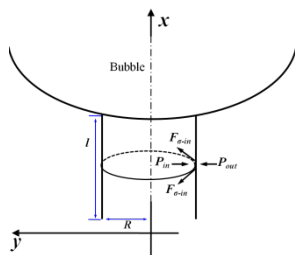

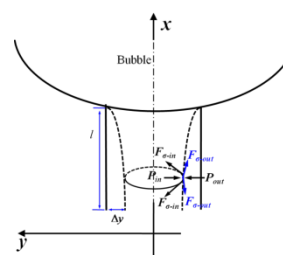Fig.4 Force analysis on stable cylindrical bubbl   Fig. 5 Force analysis on unstable cylindrical bubble

Pinch-off stage. When bubble neck's length is bigger than $\sqrt{2}R_o$, the bubble will go into detachment stage, as shown in Fig.6. Cylindrical version of the general Rayleigh-Plesset equation can be used to describe bubble dynamics near the pinch region

$$\rho_{ext}[(\ddot{R}R + \dot{R}^2)\ln\frac{R}{r} + \frac{1}{2}\dot{R}^2] = [P_{out} - P_{in}] + (\frac{\sigma}{R} - \frac{\sigma}{R_{out}}) \qquad (1)$$
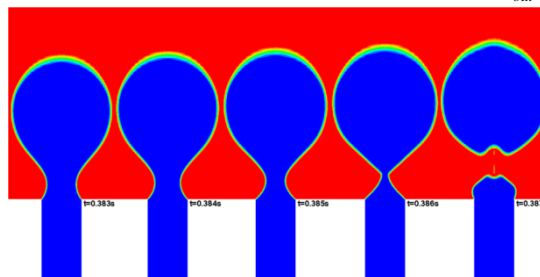

Fig. 61 Bubble pinch-off

But unknown r in $\ln\dfrac{R}{r}$ leads to the equation can not be solved. We try to give appropriate value of r through simulation. We could obtain bubble profile and pressure field with time from simulation, as shown in Figure 7. From pressure field, P_{out} and P_{in} is known, which are both perpendicular to the bubble surface. From bubble profile, curvature of the neck can be got and thus surface tension $\dfrac{\sigma}{R}, \dfrac{\sigma}{R_{out}}$ is known where σ is 0.07 for water. As a result, the right side of the equation in simulation can be determined. To left side of the equation, the minimum radius of the neck R_{min} is the minimum value of Y (bubble profile) in Figure 7. So R_{min} and its variation $\dot{R}_{min}$, $\ddot{R}_{min}$ can be obtained. If r is given, the left side of the equation at R_{min} can be known . When both sides of the equation are close, the value of r is what we want. This is the idea of getting appropriate r in this paper.

According to $\ln\dfrac{R}{r}$ in the equation, r is assumed as $r = R \bullet e^n$, $n = 1, 1.5, 2, 3, 4$. The comparison between the two sides of the equation at different r is shown in Figure 8. We can see that value of both sides are close when n=1.5~2. So we think that r in cylindrical version Rayleigh-Plesset equation for bubble pinch-off is about $R \bullet e^{1.5} \leq r \leq R \bullet e^2$, ie $4.5R \leq r \leq 7.4R$. Eq.(1) can be written as

$$\rho_{ext}[C \bullet (\ddot{R}R + \dot{R}^2) + \frac{1}{2}\dot{R}^2] = [P_{out} - P_{in}] + (\frac{\sigma}{R} - \frac{\sigma}{R_{out}})$$

(2)

where $4.5 \leq C \leq 7.4$. Eq.(2) could be used to predict dynamic behaviors of gas bubble formation in water.
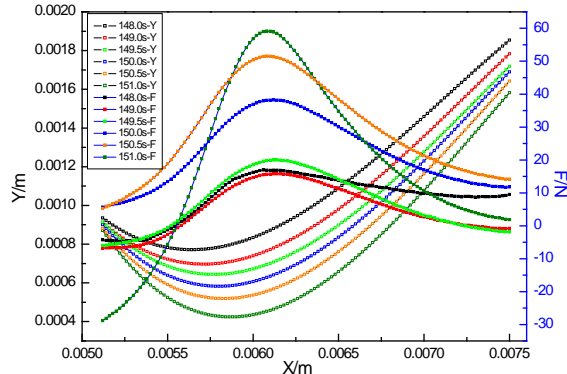

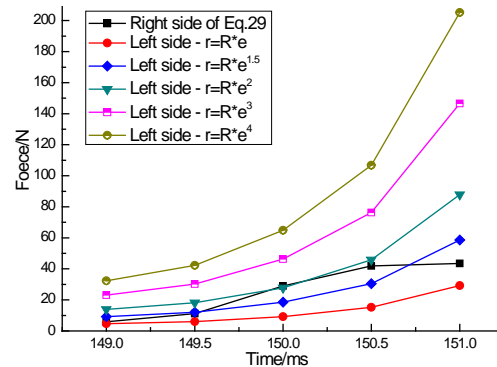Fig.7 Profile of bubble neck and resultant force with time

Fig. 8 Comparison between the two sides of the equation at different r

4. Conclusions

Experiment and simulation of bubble formation on submerged orifice under constant gas flow rate were taken in this paper. Compressible large eddy simulation combined volume of fluid (VOF) was adopted in simulation and results were validated by experiment. Bubble formation is divided into three stages in this paper, expansion stage, elongation stage and pinch-off stage.

In expansion stage, the bubble grows radially due to the incoming gas flux, but the bubble base remains attached to the orifice. The growth rate of bubble volume nearly equals to the gas flow rate. As gas injected, the spherical bubble will go into the elongation stage when the downward resultant force is lager than upward resultant force. In this stage, the bubble lifts away from the orifice, but still attached to it through a neck, which is thought to be a stable cylindrical bubble. When bubble neck's length is bigger than $\sqrt{2}$ times of the orifice radius, the bubble will go into pinch-off stage. Cylindrical Rayleigh-Plesset equation can be used to describe the pinch-off stage. Parameter r in the equation is given as $R \bullet e^{1.5} \leq r \leq R \bullet e^2$ based on analysis of simulation results in this paper.

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