Quasi-static single bubble formation behaviour: interaction with adjacent induced flow structure

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Abstract. Single bubble formation behaviours which develops from submerged nozzle under the quasi-static mode in stagnant deionized water in a rectangular column are studied. Bubble formation behaviours are captured by a digital high-speed camera and information of the induced adjacent flow field is synchronously obtained via the particle image velocimetry (PIV) system. Interactions of induced bubble adjacent flow patterns with bubble formation behaviours are investigated at each stage of a three-stage bubble formation model. Results indicate that recirculation of the continuous phase near the bubble base accelerates rapid detachment of the bubble and the dynamic pressure variation in the liquid induced by bubble behaviours is the main reason why such flow pattern appears.

1. Introduction
Bubble formation on submerged orifices plays a significant role throughout chemical, biomedical, nuclear and metallurgical industries. Dynamic bubble formation modes, including static, dynamic and turbulent under various bubbling conditions, were firstly illustrated by McCann and Prince [1]. The static mode is the most familiar in less turbulent bubbling conditions [2]. Numerical investigations [3-7] have been reported in order to deeply understand the quasi-static bubble formation and its dynamic behaviors. Continuous variations of a developing bubble, such as dynamic changes at the gas-liquid interface, the bubble volume growth rate and the bubble formation rate, attracted the most attention [3].

Initially, various models were set up theoretically under idealistic assumptions in order to build equation sets to correlate the triple line shape, detachment volume and detachment time with several operation parameters [4, 5]. Quasi-static bubble formation was firstly assumed to be a single-stage process in which it remains spherical and the liquid circulation is negligible [6, 7]. Later on, a two-stage (expansion and detachment) model was proposed by Ruff [8] who predicted the detachment volume and the duration of the second stage.

Periodical dynamic bubble formation behaviors have been captured and illustrated through experimental methods [9, 10]. Based on observations, the quasi-static bubble formation can be referred as a three-stage variation process which is illustrated as the expansion stage, elongation stage and detachment stage in terms of the bubble shape variation [11]. Recent research show that force equilibrium and momentum balance result in dynamic bubble behaviors during the bubble formation process [12, 13]. For instance, buoyance, capillary force, surface tension, dynamic forces including inertia and viscous forces work together on a developing bubble [12, 13]. Bari and Robinson [14] proposed formulas for each kind of force and evaluated local dynamic pressure of the adjacent liquid.
flow based on the Young-Laplace equation. Vafaei and Wen [15] and Gharedaghi et al. [16] treated bubble as a combination of several ‘slices’ or ‘sections’ along the vertical direction and analyzed the stress condition of each ‘slice’ followed by integration of them to obtain the characteristics of the whole interface. Furthermore, in both of their work dynamic pressure of the continuous phase was taken into consideration, which gained more insights for the bubble study.

In the present work, experiments of visible induced flow field measurement are carried out via the particle image velocimetry (PIV) system. Instantaneous induced pressure distribution of bubble adjacent flow is re-calculated via the flow velocity information. Besides, interactions of the induced adjacent flow with a developing bubble are studied and the mechanism of quasi-static single bubble formation is analyzed through a force balance model considering effects of the induced adjacent flow.

2. Experimental apparatus

2.1. Bubble formation and departure

A schematic diagram of the experimental apparatus, PIV system and a high-speed shadow image system are shown in Figure 1.

![Figure 1. Schematic diagram of the experimental apparatus.](image)

Table 1. Operation conditions.

| Bubble Behaviour      | \( \mu_o \) (10^{-3} Pa*s) | \( D_o \) (mm) | \( Q \) (ml/h) |
|-----------------------|---------------------------|---------------|---------------|
| Quasi-static formation| 1.005                     | 2.2, 2.5, 3.0 | 180/140/120/100/80 |
2.2. Shadow image and PIV system
Dynamic bubble formation behaviors are captured by a digital high-speed camera (Phantom-V711) with a frame rate of 1200fps. In order to obtain sharp images of the bubble outline, a tender light cloth and a Light Emitting Diode (LED) illuminant are set up behind the tank. Meanwhile, a PIV system is synchronized with this high-speed camera via a synchronizer (610036, TSI). The whole PIV system consists of a Charge-Coupled Device (CCD) camera (630019, TSI) with a frame rate of 15fps, a double pulsed Nd: YAG laser (YAG200-15-QTL, EverGreen) emitting light with a wavelength of 532nm and an articulating arm light guide. Fluorescent tracer particles (1.05g/cm³ in density and 20μm in diameter) is added into the flow. Bubble behaviour shadow images are processed by a designed MATLAB program. Background information and noise pixels are removed. Besides, bubble characteristics, such as timing parameters and bubble volume, are calculated and the bubble outline is extracted. Particle images of the induced flow field are processed and analysed by commercial software (TSI Insight 4G).

3. Results and Discussions

3.1. Bubble formation behaviours
Fig. 2 shows a force equilibrium model of quasi-static bubble formation proposed by Bari and Robinson [14], where \( F_b \) is partial buoyancy force, \( F_{cp} \) is the contact pressure, \( F_c \) is the capillary force and \( F_d \) is the dynamic force including inertial force and viscous force.

Quasi-static bubble formation process is a periodic process. Fig. 3 shows the bubble volume variation at a gas flow rate of \( Q=180\text{ml/h} \) from the needle nozzle with a diameter of 3.0mm. At a constant gas flow rate, the bubble volume increases linearly with time and there is a waiting period at the beginning. The bubble grows sluggishly at the waiting period as a result of high contact pressure and capillary force. With the bubble evolution, the buoyancy augments to resist the absorption by the orifice and the bubble volume increases constantly during this periodic progress. Therefore, the whole bubble formation cycle includes a waiting time \( t_w \) where bubble is tiny in the needle and a developing time \( t_d \) where bubble grows with the injected gas.

![Fig. 2 Force equilibrium of quasi-static bubble](image_url)
Fig. 3 Bubble volume variation during its formation period.

In this periodic bubble formation progress, the shape of bubble changes with its volume increasement. At the initial stage of bubble formation on the submerged orifice, the bubble needs to overcome hydrostatic pressure, capillary force and surface pressure at the gas-liquid interface. When the gas-phase pressure at the air outlet increases to a certain extent, the bubble begins to grow. Figure 4 depicts the dynamic performance of the bubble formation process at different moments captured by the shadow photography technique with a needle diameter of 3.0mm and a gas flow rate of 180ml/h. As can be seen from Figure 4, the bubble formation process can be divided into three stages.

$t/\tau_f = 0.093 - 0.256$: At this stage, the bubble volume is small. The increasing bubble contact angle leads to an increasing capillary force. The bubble behaves approximately as a hemispherical sphere and continues to expand.

$t/\tau_f = 0.256 - 0.852$: The bubble is in the upward elongation state and the bubble diameter is larger than the aperture of the needle tube. Bubble is begin affected by the buoyancy to resist surface tension.

$t/\tau_f = 0.946 - 0.992$: There is a relatively obvious contraction at the bubble root, which is called 'necking'. Bubble is mainly affected by the buoyancy. The bubble centroid rises appreciably.
Figure 6 shows the height variation of a developing bubble versus an aspect ratio defined as $E = h/w$, which indicates the deformation level of the bubble shape. At early stage of the bubble growth cycle, with continuous injection of air flow, the bubble rapidly changes from a flat shape to a nearly spherical shape. After $t/t_d = 0.33$, bubble enters the elongation stage and the shape changes slowly. After $t/t_d = 0.82$, bubble rises obviously in the necking stage, which is shown as a long ellipsoid until it breaks out from the needle.

Bubble detachment volume $V_d$ is also an important parameter in the study. Figure 6a shows the detachment volume of bubbles from needles with different diameters. Tate [6] gives a prediction model for the detachment volume in the quasi-static mode:

$$V_d = \frac{2\pi r \sigma}{\rho g (\rho_g - \rho_l)}$$

In this study, under conditions of $Q=80, 120$ and $160$ml/h, bubbles generated by needles with the same diameter kept almost the same detachment volume and had no significant difference in Tate volume. However, experimental results are slightly greater than the Tate volume, which may be because the Tate prediction model only takes bubble surface tension for the adsorption effect into consideration. In a real experimental process, contact pressure, inertia force and viscous force all perform for the adsorption effect.

Bubble timing parameters are shown in Figure 6b. When $Q=40$–$80$ml/h, waiting time decreases significantly, and then the waiting period decreases slowly with increasing the gas flow rate. When the flow rate is high, bubble forms very quickly. Moreover, the gas flow can effectively resist the surface tension and capillary adsorption, so that the waiting time is shortened.

3.2. Bubble induced flow structure

Bubble induced flow structure was studied in this section, under the condition of $D_o=3.0$mm, $Q=180$ml/h, by PIV analysis is carried out on particle images. The velocity distribution of adjacent flow at different formation stages are shown in Figure 7. Different morphologies are displayed and the characteristics of the gas-liquid interface movement also vary in the expansion stage, elongation stage and necking stage. These differences lead to various flow characteristics of the flow field adjacent to the bubble.
Figure 7. Induced flow velocity field under different stages of the bubble formation process.

In the expansion stage, bubble begins to emerge from the needle. It is small in size with a hemispheric shape and develops within the needle edge. It can be observed in Figure 7 a-c that at the moment of $t/t_d = 0.106 \sim 0.241$, the flow field is basically at rest and there are only microscopic radial flows around the bubble. When $t/t_d = 0.106$, the wake of the leading bubble remains above the developing bubble. The induced wake of the leading bubble would ‘suck in’ the trailing bubble, thus promoting the bubble development to the next stage. The entire flow field flows in an orderly manner following the wake of the leading bubble, and only turns at the bubble's shoulder. This feature has a correlation with the morphology and dynamic changes of bubble in the expansion stage.
Figure 8. (a) Velocity streamlines of the liquid flow at the necking stage (D₀=3.0mm); (b) Velocity streamlines near the bubble at the same stage (D₀=1.6mm). Adapted from Babu and Das [18].

In the bubble elongation stage, the bubble mainly moves vertically upward. It shows an approximate ‘hemisphere plus cone’ shape and develops beyond needle edge. As shown in Figure 7 d-f, the wake of the leading bubble vanished. The bubble induced flow field range increases longitudinally, and the rapid elongation of the bubble’s edge pushes the surrounding flow field upward. Near the bubble’s maximum radius, a small-scale flow field moves diagonally above the bubble. The whole flow structure further promotes bubble’s rise and leads bubble to its neck. The entire flow field starts to move in the horizontal direction at the bubble elongation stage. Meanwhile the influence of the bubble shoulder on the liquid flow becomes obvious and the reflux trend initially appears at the position of bubble maximum radius.

In the bubble necking stage, the bubble height change is no longer obvious, and the bubble root necks. As can be seen from Figure 7 g-i, the bubble-induced flow field range is further expanded. At the bubble top, the flow field diverges to the outside of bubble, and the backward flow which looks more obvious occurs from bubble shoulder to the neck. The backward flow scale is apparently larger than that of the previous stage. Near the interface, the backflow velocity is obviously larger than that of other regions, which is due to the upward movement of the maximum radius and it drives the liquid rise quickly at the interface. From the streamline diagram of the moving liquid corresponding to this stage in Figure 8a, it can be found that the liquid at the bubble neck flows along the neck, which accelerates the bubble necking process, thus clips the bubble and makes bubble quickly detach from the needle.

Babu and Das [18] conducted experiments to study the effects of surfactants on the dynamics of bubble growth and detachment from a submerged orifice in deionized water and deionized water mixed with non-ionic surfactant Triton X-100. The flow field structure of the bubble generation induced flow and its relationship with the surfactant concentration were reported. Figure 8a, 8b compares the flow pattern of adjacent flow at necking stage in the present study and Babu’s work. For the orifice with an internal diameter of 1.6mm, similar flow patterns are displayed with this present study. However, in the necking state, the eddy flow at the bubble maximum radius was not observed in their work. In the present study, for the needle with a larger diameter, relatively obvious eddy flow is observed in the flow fluid near the position of bubble maximum radius, which is due to the reason that when bubble volume becomes large, changes of the gas-liquid interface results in an obvious upward movement of the maximum bubble radius. The interface movement in a larger scale pushes the adjacent liquid harder and a vortex flow pattern appears when this flow meets the radial flow at the bubble shoulder.
3.3. Instantaneous induced pressure field of the induced flow
Based on the analysis of interactions between bubble behaviours and the induced flow in section 3.2, a
conclusion was drawn that, at the necking stage of the quasi-static bubble formation process, effects of
the adjacent flow become dominant. Therefore, a methodology was developed to recalculate the
instantaneous pressure via the velocity information obtained from the PIV system. Figure 9 depicts the
instantaneous pressure field of the induced flow at the necking stage. In the bubble rising region above
the bubble top, the pressure of the liquid is lower, so the liquid would flow upward continuously. At the
tank wall where is far away from the bubble, the induced pressure is almost zero, which implies the
dynamic bubble behaviours do not have effects on the flow field in such a long distance. The induced
pressure is larger near the gas-liquid interface in the bubble shoulder region where the vortex flow centre
appears. While in the bubble necking region, the liquid field pressure is small, which indicates a
backward flow of liquid to move towards the bubble neck and accelerates the necking stage.

![Figure 9](image-url)

Figure 9. Instantaneous induced pressure distribution of the induced flow at the necking stage.

4. Conclusion
The quasi-static bubble formation behaviours in deionized water and the induced flow field were
experimentally investigated. Diameters of the needle tested were 2.2mm, 2.5mm and 3.0mm, and the
gas flow rate was between 80–180ml/h. Bubble formation behaviours are captured by a digital high-
speed camera utilizing the shadow image technology and a PIV system is applied to measure the adjacent
induced flow filed. The instantaneous induced pressure of liquid is re-calculated based on the velocity
information. Conclusions are listed as follows:

(1) The quasi-static bubble formation progress is a periodic process, which can be defined in a
three-stage model.

(2) The induced flows show different structure patterns respectively at those three stages. The
effect of the wake of a leading bubble remains at the expansion stage. Besides, a vortex flow appears
near the shoulder of the bubble at the elongation and necking stage. The backward flow accelerates the
necking stage of the bubble formation process.

(3) The instantaneous induced pressure caused by the movement of the interface is the main reason
why the vortex flow occurs near the bubble.

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