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BUBBLE FORMATION IN SHEAR-THINNING FLUIDS: LASER IMAGE MEASUREMENT AND A NOVEL CORRELATION FOR DETACHED VOLUME

Article Highlights
• The formation process of a minute bubble was acquired accurately by laser image technique
• A bubble formed in shear-thinning fluid presents slim shape due to the fluid’s memory effect
• The detached volume rises with solution mass concentration, gas chamber volume and orifice diameter
• A novel correlation of detached volume was developed and agreed better than previous models

Abstract
A laser image system has been established to quantify the characteristics of growing bubbles in quiescent shear-thinning fluids. Bubble formation mechanism was investigated by comparing the evolutions of bubble instantaneous shape, volume and surface area in two shear-thinning liquids with those in Newtonian liquid. The effects of solution mass concentration, gas chamber volume and orifice diameter on bubble detachment volume are discussed. By dimensional analysis, a single bubble volume detached within a moderate gas flowrate range was developed as a function of Reynolds number, Re, Weber number, We, and gas chamber number, Vc, based on the orifice diameter. The results reveal that the generated bubble presents a slim shape due to the shear-thinning effect of the fluid. Bubble detachment volume increases with the solution mass concentration, gas chamber volume and orifice diameter. The results predicted by the present correlation agree better with the experimental data than the previous ones within the range of this paper.

Keywords: laser image, bubble formation, shear-thinning fluid, empirical correlation.

The phenomenon of bubble formation and motion in non-Newtonian fluids is frequently encountered in chemical, biochemical, environmental, petrochemical processes owing to its advantages of high-efficiency interphase contact [1,2]. In typical applications in bubbly flow, such as bubble columns and bioreactors, single bubble formation has a significant impact on the mass transfer, heat transfer and chemical reactions between gas and liquid phases, since bubble generation directly determines the bubble characteristics, such as bubble shape, volume, rising trajectory and production frequency. However, the mechanism of bubble formation remains far from fully known due to its inherent complexity. Therefore, an adequate understanding of single bubble formation in non-Newtonian fluids is of great importance to gain insight into bubble swarms dynamics as well as to optimize the design of bubble columns.

Previous research revealed that bubbles in non-Newtonian fluid exhibit various features due to the fluid inherent complexity compared with Newtonian fluid [3]. Earlier investigators mainly focused on the
experimental measurement of bubble volume [4-6]. Then, Miyahara et al. [7] proposed a simple spherical model for bubble formation. Terasaka and Tsuge [8-10] concentrated on the several influence on bubble volume respectively. Li [11] and Li et al. [12] predicted the instantaneous size, shape and frequency of generating bubble. Martin et al. [13,14] studied further the growing and ascending features of the bubble in both Newtonian and non-Newtonian fluids. Peyghambarzadeh et al. [15] explored experimentally bubble departure diameters in pure water and three different electrolyte solutions. Venkatachalam et al. [16] developed a new prediction model of gas holdup for a wide range of operating conditions in a homogeneous flow regime. Recently, Vélez-Cordero and Zenit [17] devoted to the bubble cluster formation in power-law shear-thinning fluids. From micro-scale to macroscale, Dietrich et al. [18] revealed the various mechanisms governing the bubble formation. However, most of these investigations are either limited to Newtonian fluids, or insufficient in overall consideration of the essential parameters, which include density, apparent viscosity, surface tension, gas flowrate, orifice diameter and the volume of gas chamber. However, as a crucial parameter in determining bubble formation model, the gas chamber volume is missing in these investigations. Furthermore, the mechanism of bubble growth and detachment remains far from settled.

Despite a large number of studies on bubble formation in non-Newtonian fluids, quantitative measurement of bubbles remains a major challenge to the experimentalists, especially for semi-transparent liquid systems. Two types of experimental means, including mainly intrusive and non-intrusive techniques, are generally employed [19]. However, intrusive techniques, such as conductivity probes [20], optical fiber probes [21], ultrasound probes [22] and hot film anemometry [23], inevitably disturb the flow field and become invalid for the small difference of the measured indexes between the gas-liquid phases. By contrast, non-intrusive techniques overcome the disadvantage of interfering with the flow field and are applied widely in various forms [24-26]. Among these non-intrusive techniques, high-speed cameras are employed extensively owing to their capability of catching instantaneous bubble behavior and continuously recording. Obviously, this method requires transparent liquids and relatively low gas holdup in the near wall region.

In this work, a laser image system was set up for determination of the bubble formation process at a single submerged orifice. Bubble formation process in shear-thinning fluids was directly visualized and recorded in real-time by CCD camera and computer by means of He-Ne laser as the light source using beam expanding and light amplification technology. Bubble generation mechanism was investigated through comparing bubble shape evolution in aforementioned fluids with that in Newtonian fluid, and the influence factors on detachment volume of the bubble were determined experimentally. Further, by taking both fluid physical properties and all operating conditions into account, a correlation for the detachment volume of single bubbles formed in a stagnant shear-thinning liquid was developed based on the dimensional analysis of various kinds of parameters.

**EXPERIMENTAL**

**Apparatus and conditions**

The experiments were conducted in a square Plexiglas tank (inner dimensions: 0.15 m width, 0.5 m high) filled with aqueous phases, as shown in Figure 1. Bubbles were generated by injecting a volumetric flow of nitrogen through a replaceable orifice drilled in the centre of the Plexiglas plate (0.15 m×0.05 m×0.01 m), located inside the tank 0.1 m above the bottom. Gas flow rate could be displayed accurately by the rotameter calibrated through adjusting a regulation valve, and a gas chamber was applied to avoid any fluctuations induced by bubble formation and detachment. Therefore, bubbles were always generated periodically from a submerged orifice.

In the image measurement system, the laser beam emitted by He-Ne laser source passed through a spatial filter and a collimating lens, then became a parallel beam, and subsequently passed through the experimental tank filled with liquids. The tank was carefully adjusted to keeping the bubble at the centre of the beam spot, and the process of bubble growth and detachment was magnified properly and imaged on a frosted glass screen by an amplifying lens. Meanwhile, these images were saved on the hard disk by the CCD camera (resolution 640×480 pixels, sampling frequency 25 fps) and picture collection card. In our experiment, the bubble always grew symmetrically along its vertical axis passing through the orifice center. Thus the solid of revolution with regard to the boundary of the recorded bubble image was obtained, and was then divided into many elements of cone and truncated cone. Consequently, the bubble volume and surface area could be calculated by integrating above the elements based on a reference scale calibrated previously. Especially, bubble characteristics were finally acquired by averaging the
results calculated three times using self-developed treatment software. It is noted that assuming a maximum error of ±1 pixel in the determination of the contour of the bubble yields that the average uncertainty in the diameter calculation ranges from 2.3 to 4.7% for bubble volume and from 1.6 to 3.4% for surface area.

The experiments were implemented under following conditions: orifice diameters \(d_o\) 1.0, 1.5, 2.0 mm; chamber volume \(V_C\) 30, 90, 270 mL; gas flowrate \(q\) 0.1–1.0 mL/s; carboxymethylcellulose (CMC) aqueous solutions 0.8, 0.9, 1.0%; polyacrylamide (PAM) aqueous solutions 0.25, 0.50, 0.75%. Note that \(q\) refers to the gas flow rate into the gas chamber. The rheological characteristics, surface tension and density of the solutions involved above were measured by a StressTech Rheometer (Reologica Instruments AB, Sweden), dynamic surface tension apparatus (DCAT21, Dataphysics, Germany) and pycnometer. Moreover, in order to compare the bubble shape evolution in Newtonian fluid, 99.7% glycerol aqueous solution was used and its physical properties were measured. The shear-thinning behaviors of these solutions could be described adequately by a power law model [11], as shown in Eq. (3), within this experimental range of shear rate. Therefore, the rheological parameters of all solutions were obtained by regression of the measured data and the results are shown in Table 1.

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Density (\rho) / kg m(^{-3})</th>
<th>Surface tension (\sigma) / mN m(^{-1})</th>
<th>Consistency (K) / Pa s(^n)</th>
<th>Flow index, (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.80% CMC</td>
<td>1002.3</td>
<td>71.20</td>
<td>1.738</td>
<td>0.713</td>
</tr>
<tr>
<td>0.90% CMC</td>
<td>1002.6</td>
<td>70.40</td>
<td>2.904</td>
<td>0.664</td>
</tr>
<tr>
<td>1.00% CMC</td>
<td>1003.6</td>
<td>69.70</td>
<td>3.629</td>
<td>0.646</td>
</tr>
<tr>
<td>0.25% PAM</td>
<td>999.38</td>
<td>72.86</td>
<td>0.092</td>
<td>0.663</td>
</tr>
<tr>
<td>0.50% PAM</td>
<td>1001.4</td>
<td>71.98</td>
<td>0.212</td>
<td>0.592</td>
</tr>
<tr>
<td>0.75% PAM</td>
<td>1002.8</td>
<td>69.54</td>
<td>0.344</td>
<td>0.555</td>
</tr>
<tr>
<td>99.7% GL</td>
<td>1260.2</td>
<td>63.30</td>
<td>1.420</td>
<td>1.000</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSIONS

Bubble shape evolution comparison

Figure 2 presents the evolution comparison of the bubble shapes in two shear-thinning fluids and

![Figure 2. Bubble shapes in shear-thinning and Newtonian fluids at different time: a) 1.0% CMC; b) 0.75% PAM; c) 99.7% GL.](image-url)
Newtonian fluid under the same condition: \( q = 0.15 \) mL/s, \( \delta = 2.0 \) mm and \( v_c = 270 \) mL. Note that the reference time (\( t = 0 \)) is defined as the moment when a bubble just detaches from the orifice, and that the scale for image sequences is corresponding to the image of the orifice connected with the growing bubble. It is indicated that in both non-Newtonian fluids, bubble formation experiences expansion stage and stretching stage respectively. In the first period, the bubble surface expands spherically in radial direction owing to the dominant role of surface tension. However, the influence of buoyancy on the bubble becomes important gradually with the growth of the bubble. Subsequently, the bubble is elongated vertically to an inverted teardrop-like shape under the combined action of the increasing buoyancy and resistance until its detachment from the orifice.

Furthermore, three main differences between two kinds of shear-thinning fluids and Newtonian fluid are acquired:

1. In contrast with the inverted teardrop-like shape in glycerol solution, the bubble surface located between the maximum horizontal diameter and the tail tip is pulled downward and becomes thin due to the existence of reduced viscosity after the passage of bubbles in non-Newtonian shear-thinning fluid, or so-called the wake behind the previous rising bubble [9]. Further, the above memory effect of the fluid is reinforced with the increase of bubble generation frequency because of the decrease of detached volume under the experimental condition of the same gas flow rate. Consequently, the neck of big bubble is always thinner than that of the small one in shear-thinning fluids.

2. Both instantaneous volume and surface area of the growing bubble in CMC and PAM solutions become smaller than in the glycerol solution, with the same trend as the growth rates corresponding to shear-thinning fluids and Newtonian fluid, as shown in Figure 3. In fact, the overall resistance in glycerol solution, which the bubbling needs to overcome, became larger than that in shear-thinning fluids due to its higher viscosity and density. Thus, in glycerol solution, the gas chamber pressure bubbling needs becomes large and so as the pressure difference between the gas bubble and the chamber, resulting in a large detached volume. Consequently, the bubbling frequency decreases for the same gas flow rate into the chamber. Actually, as the bubble expands further the chamber pressure begins decreasing very quickly as soon as the bubble starts to grow. However, the big overpressure in the chamber causes the bubble to form rapidly, leading to a high instantaneous gas flow rate through the orifice in Newtonian fluid with high concentration [27].

![Figure 3. Variation of bubble volume (a) and bubble surface area (b) with time.](image)

**Effect of solution mass concentration on bubble detached volume**

The effect of solutions mass concentration on bubble detachment volume is illustrated in Figure 4. The results show that the detachment volume formed in both CMC and PAM fluids increases with the solution mass concentration. The main reason lies in three aspects of solution physical properties. First, the apparent viscosity of solutions increases with the mass concentration, and the viscous drag force of the fluid surrounding the bubble blocks the growing and rising of bubble. Second, the density of the solution increases with mass concentration, which also contributes to the increase of the drag force, additionally, the mass of liquid around a bubble increases with it growth. Meanwhile, the buoyancy acted on the bubble increases, which, however, is restrained due to its small magnitude with respect to above two terms. Consequently, the growth time of bubble is prolonged. Third, the surface tension, which tends to hinder the
expansion of bubble surface, reduces slightly with the solution mass concentration, as shown in Table 1. In other words, the high mass concentration of the solution will promote bubble growth. However, Martin et al. [13,14] explained the contribution of viscosity from the viewpoint of fluid streamline. According to their reports, there exists a layer of liquid surrounding the bubble, which is directed from the bubble top to the orifice, and while this streamline reaches the gas-liquid-plate point, the dynamic pressure exerted by it will lead to the bubble constriction. As fluid viscosity increases, the velocity of the liquid layer will be lower, allowing the bubble to grow further before the dynamic pressure on the three-phase point is high enough to cut the bubble neck.

Figure 4. Effect of solutions concentration (a: PAM, b: CMC) on bubble detached volume ($d_0 = 1.0 \times 10^{-3} m$, $v_c = 30 \times 10^{-6} m^3$).

Effect of chamber volume and orifice diameter on bubble detached volume

As is well known, the mechanism of bubble formation depends greatly on its intake mode [28], which is closely related to the gas chamber volume. Previously, Satyanarayan et al. [29] found that bubble volume almost increased equivalently with the gas chamber size, however kept constant as the chamber size further added. Besides, Terasaka et al. [8] reported that this effect of gas chamber volume on bubble size reduced with the increase of gas flowrate. Particularly, bubble formation mode could be generally classified into three types in terms of a dimensionless number ($N_c$) [30]. According to Satyanarayan's report, constant gas flowrate mode is drawn in the present investigation whose range of $N_c$ varies from 0.09 to 3.3. Therefore, the pressure in the gas chamber undergoes a periodic change: waiting-bubbling-waiting. There always exists a cyclical fluctuation in the pressure in the gas chamber, but its amplitude goes down with the increase of gas chamber volume. Thus, the greater chamber brings higher average pressure, which leads to the larger driving force for bubble formation, consequently resulting in the bigger bubble, as shown in Figure 5a.

Figure 5. Effect of chamber volume (a: 0.8% CMC, $d_0 = 1.5 \times 10^{-3} m$) and orifice diameter (b: 1.0% CMC, $v_c = 30 \times 10^{-6} m^3$) on bubble detached volume.

Bubble detachment volume varies with the gas flowrate under different orifice diameter conditions as
shown in Figure 5b. It is evident that the bubble detached volume gradually increases with the orifice diameter, which is consistent with the reports [31]. However, Terasaka et al. [10] reported the same result for relatively high gas flowrate but the contrary result for relatively low gas flowrate. This implies that the influence of orifice diameter becomes more complicated because the rheological behavior of the non-Newtonian fluids is related closely to the gas flowrate.

Dimensional analysis and correction of bubble detached volume

The behavior of bubble formation in non-Newtonian fluids is dominated mainly by such parameters as gas flowrate, gas chamber volume, orifice diameter, as well as density, viscosity and surface tension of gas-liquid systems. The conventional approach for correlating the bubble detached volume is to obtain an equation between the bubble volume and only parts of these parameters in Newtonian fluids. This work has made an attempt to develop the dimensionless corrections to predict bubble volume $V_b$ in non-Newtonian fluids based upon the Buckingham Pi theorem [32]. Due to $\rho_g \ll \rho$, $\mu_g \ll \mu$, a general function of bubble detachment volume $V_b$ can be expressed mathematically as the relevant fluid physical properties and operating condition:

$$V_b = f(\rho, \mu, (K, n), \sigma, q, d_o, v_c)$$

(1)

where $\rho$, $\mu$, $\sigma$, $q$, $d_o$ and $v_c$ are density, apparent viscosity, surface tension, gas flowrate, orifice diameter and the volume of gas chamber, respectively.

Finally, the application of the Buckingham Pi theorem of dimensional analysis to the present case gives following expression of $V_b$:

$$\frac{V_b}{d_o^3} = \alpha(\pi / 4Re)^{\beta_1} (\pi^2 / 16We)^{\beta_2} (V_c)^{\beta_3}$$

(2)

In particular, the average gas flow velocity $u_o$ is calculated by the equation $4q/(\pi d_o^2)$. According to the intermediate region of shear rate, the power law model is used to describe the rheology of fluids, and thus:

$$\mu_i(K, n) = K(K)^{n-1}$$

(3)

Due to the difficulty of experimental measurement for the shear rates of bubble growing in power law fluids, it is obtained through calculating $u_i/d_o$ approximatively by referring literature [33], then the viscosity of fluids could be expressed as:

$$\mu_i = K(u_i/d_o)^{n-1}$$

(4)

In fact, Reynolds and Weber numbers in terms of orifice diameter are respectively expressed:

$$Re = \frac{\rho_g d_o^2 u^2}{\mu}$$

$$We = \frac{\rho_g u^2 d_o}{\sigma}$$

(5a)

(5b)

It should be noted that a new dimensionless number $V_c$ related to gas chamber volume has been introduced and written in the form:

$$V_c = \frac{v_c}{d_o^3}$$

(5c)

Therefore, Eq. (2) could be rewritten in the form:

$$\frac{V_b}{d_o^3} = \beta_0 Re^{\beta_1} We^{\beta_2} V_c^{\beta_3}$$

(6a)

Finally, Eq. (6b) is obtained:

$$\frac{V_b}{d_o^3} = \beta_0 Re^{\beta_1} We^{\beta_2} V_c^{\beta_3}$$

(6b)

The constants $\beta_0$, $\beta_1$, $\beta_2$ and $\beta_3$ in the Eq. (6b) are obtained by fitting the experimental data of various CMC and PAM concentrations solutions under a variety of conditions using the least square method and the result is shown in Table 2.

| Table 2. The constants in dimensionless correlations of $V_b$ |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Constant $\beta_0$ | $\beta_1$ | $\beta_2$ | $\beta_3$ |
| Value 0.33249 | -0.4732 | 0.4757 | 0.5815 |

As a result, a novel correlation for the detachment volume of a bubble formed in shear-thinning fluids in present condition is acquired:

$$\frac{V_b}{d_o^3} = 0.33249 Re^{0.4732} We^{0.4757} V_c^{0.5815}$$

(7)

The validity of Eq. (7) correlation is shown by plotting $V_b/d_o^3$ against $Re$ for various systems against $Re$ in Figure 6a. The average relative error between the predicted and measured values is below 7%.

To estimate the reliability of the proposed correlation, the following correlations are included. In a wide experimental range of liquid height 0.6-2.1 m, gas flowrate 0-15 mL/s, orifice diameter 0.5-4.0 mm, Jamialahmadi et al. [34] made an effort on bubble formation in water as well as the solutions of water with methanol, ethanol, propanol, glycerol and potassium chloride. Then, a nonlinear correlation for bubble diameter in terms of orifice diameter as in Eq. (8) was generated by using radial basis function (RBF) neural
network architecture. Recently, by dividing the bubble formation into the constant volume regime and the growing volume regime, Wang et al. [35] proposed an improved correlation for bubble volume in air-water systems as in Eq. (9):

\[
\frac{d_b}{d_o} = \left[ \frac{5.0}{Bo^{0.08}} + \frac{9.261Fr^{0.36}}{Ga^{0.39}} + 2.147Fr^{0.51} \right]^{1/3}
\]

(8)

\[
V_b = 0.934 \frac{\pi \sigma d_o}{g(\rho_i - \rho_g)} + 1.2 \frac{q^{1.128}d_o^{0.18}}{g^{0.564}}
\]

(9)

The comparison between correlations given by Eqs. (7)-(9) is presented in Figure 6b within the range of 0.047 < \(Re\) < 5.71, 0.028 < \(We\) < 32.58, and 3.75x10^2 < \(V_c\) < 2.7x10^5. It should be noted that the experimental volume is taken from our experimental results, and the ranges of three dimensionless variables are based on the whole experimental data in this work. It is clearly seen that the predictions from both Eqs. (8) and (9) are in considerable agreement with the experimental data within an average error 30%, and the present model is more accurate than Eqs. (8) and (9) with an average error near 10%. Moreover, a further comparison of the present model with experimental data from Jamialahmadi et al. [34] and Wang et al. [35], also shows a high prediction accuracy of Eq. (7) with error less than 16%, as demonstrated in Figure 7. It has been proved that by applying the proposed correlation, we can predict bubble detachment volume with a reasonable accuracy within the experimental condition.

![Figure 6](image1.png)

**Figure 6.** Validity (a) of Eq. (7) and its reliability (b) by comparison with the values calculated from Eqs. (8) and (9).

![Figure 7](image2.png)

**Figure 7.** Comparison of the present correlation with the experimental data from Jamialahmadi et al. [33] and Wang et al. [34].

### CONCLUSION

We applied a laser image method combined with computer processing technique to study experimentally single bubble formation in shear-thinning solutions under constant gas flow rate condition. The characteristics of a growing bubble in non-Newtonian fluid have been compared with that in Newtonian fluid, and the effects of solution mass concentration, gas chamber volume and orifice diameter on the bubble detachment volume were discussed. The results indicate that the bubble formation process can be divided into spherical expansion and vertical elongation two stages [36], which are mainly governed by surface tension and buoyancy force, respectively. A bubble formed in non-Newtonian fluid appears slim in shape due to the shear-thinning effect of present solutions compared with that in Newtonian fluid. The bubble detached volume in both studied fluids increases with the mass concentration of solution, chamber volume and orifice diameter. Based on the dimensional analysis on the various comprehensive parameters, a new correlation is developed to predict the detached volume of bubble in shear-thinning fluid.
fluids within the range of \( 0.47 < Re < 5.71, 0.028 < We < 32.58 \) and \( 3.75 \times 10^3 < V_c < 2.7 \times 10^5 \). It has a better agreement with the experimental data than the previous ones since an average error deceases from 30% to 10% in the experiments.

Acknowledgements

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Nomenclature

- **Bo** Bond number in terms of orifice diameter \((= \frac{\rho g d_o^2}{\sigma})\)
- **d_c** bubble diameter, mm
- **d_o** orifice diameter, mm
- **Fr** Froude number in terms of orifice diameter \((= \frac{u_c^2 \rho}{g d_o})\)
- **g** gravitational acceleration, m/s\(^2\)
- **Ga** Galileo number in terms of orifice diameter \((= \frac{\rho \mu \sigma}{32 g d_o})\)
- **K** consistency in Power law model, Pa·s\(^n\)
- **n** index in Power law model
- **N_c** dimensionless number \((= \frac{4 \nu \rho d_o}{\pi \sigma d_o^2 P_b})\)
- **q** gas volume flowrate, mL/s
- **Re** Reynolds number in terms of orifice diameter \((= \frac{\rho u_c d_o}{\mu})\)
- **u_c** velocity in terms of orifice diameter, m/s
- **V_c** bubble chamber volume, mL
- **V_c** bubble detached volume, mL
- **We** Weber number in terms of orifice diameter \((= \frac{\rho u_c^2 d_o}{\sigma})\)

Greek Letters

- **\(\alpha\)** parameter in Eq. (2)
- **\(\beta_0\)** parameter in Eq. (6b)
- **\(\beta_1\)** parameter in Eq. (2)
- **\(\beta_2\)** parameter in Eq. 2
- **\(\gamma\)** shear rate, /s
- **\(\mu\)** gas viscosity, Pa·s
- **\(\rho\)** density, Kg/m\(^3\)
- **\(\sigma\)** surface tension, mN/m

Subscripts

- **g** gas
- **l** liquid

REFERENCES

FORMIRANJE MEHURA U PSEUDOPLASTIČNIM FLUIDIMA: ANALIZA LASERSKIH SNIMAKA I NOVA KORELACIJA ZA ZAPREMINU POČETNOG MEHURA


Nova korelacija bolje se slaže sa eksperimentalnim podacima od prethodnih u primećenim uslovima istraživanja.

Ključne reči: laserski snimak, formiranje mehura, pseudoplastični fluid, empirijska korelacija.