EFFECT OF CHAMBER VOLUME AND DIAMETER ON BUBBLE FORMATION AT PLATE ORIFICES

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Experiments were performed on bubble formation at plate orifices submerged in water for various chamber volumes. The orifices used were 0.115, 0.21, 0.325, 0.435 cm in diameter, and the cylindrical chambers were 3.4, 4.94, 7.3, and 9.9 cm in diameter. The gas flow rate ranged from 0.73 to 56.5 cm^3/s and the chamber volumes from 245 to 7358 cm^3. It was found that for the 0.115 cm orifice and in the region of bubble formation in bursts, the number of grouped bubbles in a burst increases with both the chamber volume and the chamber diameter. For the other orifices, the number of bubbles is influenced by the chamber volume and is independent of chamber diameter. The formation frequency decreases with the increase of orifice diameter and chamber volume. Weeping occurred only at the two largest orifices for moderately small chamber volumes.

INTRODUCTION

Bubble formation at orifices has been studied in the past and a review of this area is given by Kumar and Kuloor[5]. There are many factors affecting bubble formation, i.e. the orifice diameter, the gas flow rate, the chamber volume beneath the orifice, etc.

The role of chamber volume during the bubble formation process has been a subject of research since 1950, when Spells and Bakowski[12] noticed that the inclusion of a 35 l tank under the orifice influenced the size of bubbles formed. Hughes *et al.*[3] found that the effect of chamber volume on the bubble formation can not be noticed when the chamber volume is small. They defined a capacity number, N_c, as

$$N_c = \frac{4\,g(\rho_l - \rho_g)V_c}{\pi d^2 \rho_g c^2} \qquad (1)$$

where V_c is the chamber volume, d is the orifice diameter, ρ_l and ρ_g are the respective densities of liquid and gas phases, c is the velocity of sound in the gas and g is the gravitational acceleration. They concluded that the chamber volume had no effect when $N_c < 0.8$. Davidson and Amick[1] noticed that for a moderately high gas flow rates the range becomes $N_c < 0.2$. Hayes *et al.*[2] conducting experiments with a 0.318 cm orifice in the range of $Q = 0.5$–40 cm^3/s and for $V_c = 4$–4000 cm^3 found that the chamber volume does not affect the bubble size when $V_c > 800$ cm^3. They also found that the chamber diameter has no effect on the bubble size in the range of ratios of chamber diameter to the orifice diameter studied by them ($32 < D/d$ 4.5). Kupferberg and Jameson[6] and McCann and Prince[8] found that during bubble formation the chamber pressure does not remain constant. During this process, the chamber pressure increases causing the initially flat gas-liquid interface to be curved and to form a bubble. The gradual increase of bubble volume with time results in a decrease of bubble and chamber pressure. After the detachment of the bubble, the resulted chamber pressure sometimes is lower than the liquid at the orifice. This causes a liquid flow through the orifice (weeping). A theoretical model for formation of bubbles at an orifice above a finite gas chamber was developed by Kupferberg and Jameson[6]. This was successfully tested in the region of single bubble formation with experiment results taken in the range $Q = 5$–100 cm^3/s and $V_c = 200$–5000 cm^3. They found that for the 0.3175 cm orifice there is a critical volume above which there is not much influence of chamber volume on bubble volume. They[7] also proposed a model for the dynamic pressures in the bubble and within the gas chamber during their formation. In the last work, they proposed also a criterion for calculating the minimum gas flow necessary to stop weeping through the orifice. McCann and Prince[8] also developed a model to describe the bubble formation process and their theory allows for quantitative estimation of weeping rates and weep points. In addition, they conducted experiments with $d = 0.476$, 0.635 and 0.952 cm, $V_c = 2250$–28830 cm^3 and $Q = 87$–3734 cm^3/s. In a later paper[9] they described the various regimes of bubbling at a submerged orifice. Khurana and Kumar[4] proposed a theoretical model for bubble formation and successfully tested it with experimental results taken for two chamber volumes $V_c = 65$ and 600 cm^3 with $d = 0.27$ cm and $Q = 5$–20 cm^3/s. Park *et al.*[11] proposed a mechanistic model for the chamber interaction and tested it with experimental results obtained with $d = 0.121$–0.33 cm, $Q = 0.0055$–0.672 cm^3/s and $V_c = 11.7$–6000 cm^3. Another model is presented by Tsuge and Hibino[13] and is tested by experiments done with $d = 0.164$ cm, $Q = 0.5$–5 cm^3/s and $V_c = 60$–1680 cm^3. Miyahara *et al.*[10] investigated bubble formation patterns with weeping and the effect of chamber volume. They conducted experiments with $d = 0.3$–1.32 cm and $V_c = 75$–14000 cm^3. In addition to the published work on single bubble formation, researchers[2,11] have noticed that at certain flow ranges bubble formation takes place in groups (or bursts) of up to ten bubbles per group[11].

The literature review shows that although the effect of chamber volume on bubble formation has been given attention in the past, most investigators studied it either at high gas flow ranges and large orifice diameters or at small flow rates and small orifice diameters. With the exception of the work of Hayes *et al.*[2], no other work mentions the possible effect of chamber diameter to the chamber volume. The purpose of this work is to fill this literature gap by experimentally studying the effect of chamber volumes for various orifices in the flow ranges not studied so far and taking into account also the effect of chamber diameter.

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EXPERIMENTAL

Laboratory air is led through a pressure regulator, needle valve and a rotameter to the section of equipment where bubbling formation takes place. This section consists of the chamber, the liquid column and the orifice. The four cylindrical chambers used were interchangeable. They were made of plexi-glass, had a height of 94 cm and inside diameters of 3.4, 4.94, 7.3 and 9.9 cm, respectively. The air was fed at a point 4 cm below the top of each vertical cylindrical chamber. The volume of the gas in each chamber was varied by changing the height of the water inside them. In this work, 'chamber volume' is defined as the total volume of the gas in the cylinder above the liquid and the gas inside the piping up to the point where there is a large pressure drop (needle valve). The liquid column was made from plexi-glass, and it had a squared cross section 11 cm on each side. The liquid level (distilled water) was kept constant at a height of 23.5 cm above the orifice plate. Each of the four interchangeable orifices consisted of the orifice plate fastened (glued) on the orifice holder. The 1 mm in width and 3.23 mm in diameter orifice plates were made from brass. The 0.115, 0.21, 0.325 and 0.435 cm squared edge orifices were made by drilling. The orifice holders were made from brass and had a 3.23 mm diameter and a 2.5 cm height. They had passes in order to attach them on the bottom plate of the liquid column.

An average bubble volume or group total bubble volume was calculated by dividing the air flow rate by the bubble or burst (group) formation frequency, respectively. Further, the mean individual bubble volume was found by dividing the group total bubble volume by the number of bubbles per group. The gas flow rate was measured by calibrated Gilmont rotameters. The formation frequency was obtained by visually counting when the frequency was less than 5 bubbles or bursts per second and by a Mayer and Wonish 725 DIGI-BETA stroboscope at higher ones.

Experiments were conducted in the range of gas flow rates 0.73–56.5 cm^3/s and chamber volumes 245–7358 cm^3.

RESULTS AND DISCUSSION

The experimental results of this study show that bubbles are formed at the orifices either singly (one at a time) or in groups. In the last case, two or more bubbles would appear to form simultaneously. Actually, several bubbles are individually formed in rapid succession and then there is a dormant period before the next burst. This group (or burst) formation is believed to be due to the failure to reestablish a stable, sub-hemispherical gas-liquid interface after the detachment of the bubble due to high chamber pressure (high kinetic energy of the gas flow through the orifice) and the possible presence of a low-pressure wake which follows the preceding bubble[11]. The results are presented in Table 1 and in Figures 1–7. In them the bubble volume, V_b, and the bubble (or group) formation frequency, are given as a function of gas flow rate, Q, the chamber volume, V_c, the orifice diameter, d, and the chamber diameter, D. It should be noted that V_b represents either single bubble volumes when they are formed one at a time or individual bubble volumes in a group when formed in bursts. Similarly the formation frequencies are either of single bubbles or of group of bubbles, respectively.

Table 1. Bubble formation frequencies (s^{-1}) for the 9.9 cm chamber at various gas flow rates (cm^3/s), chamber volumes (cm^3) and orifice diameters (cm).

	$d\downarrow/Q\rightarrow$	0.73	1.9	3.9	8	16.1	28.7	56.5
$V_c=847$	0.115	86	95	200	567	811	994	
	0.21	70	157	228	404	568	675	813
	0.325	67	125	210	362	540	615	628
	0.435	92	222	265	350	430	494	610
$V_c=6465$	0.115	19	41	59	574	792	891	
	0.21	38	84	115	292	469	638	819
	0.325	33	69	125	200	360	511	565
	0.435	30	63	90	174	300	418	550

Effect of Q, d, and D

Group bubble formation was observed to occur mainly at low gas flow rates ($Q < 4$ cm^3/s). At higher flow rates the bubbles are formed singly. Similar group bubble formation phenomena have been observed also by others[2,11]. Figure 1 summarizes the results of the present work for the number of grouped bubbles formed in bursts at various orifice and chamber diameters and various chamber volumes. It is seen that for the smallest orifice ($d=0.115$ cm) and for $Q<4$ cm^3/s group bubble formation starts from the smallest chamber volume used (327 cm^3) and that the number of bubbles in a group increases with the chamber diameter and volume. Bubbles in groups are formed on the 0.115 cm orifice in the case of chamber diameters of 3.4 and 4.9 cm when $Q<2$ cm^3/s and in the case of chamber diameters of 7.3 and 9.9 cm

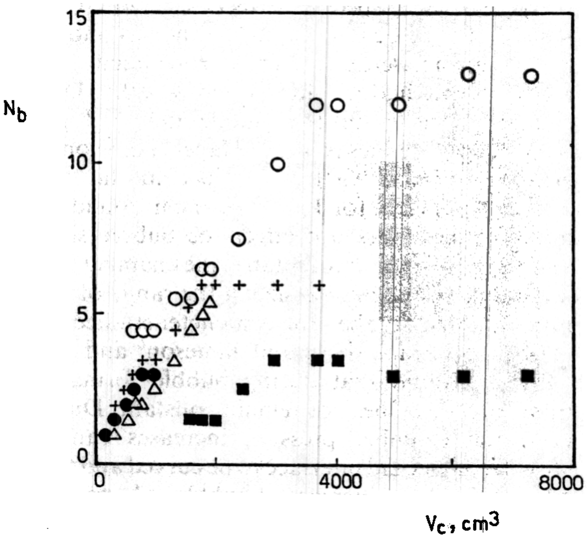

Figure 1. Number of bubbles per group (burst) vs. chamber volume for various nozzle and chamber diameters. (Note formation in groups (bursts) occurs in the region $Q<2$ cm^3/s when $d=0.115$ cm and $D=3.4$ and 4.9 cm and in the region $Q<4$ cm^3/s for the others. At greater gas flow rates, single bubbles are formed in both cases.) ● $d=0.115$ cm, $D=3.4$ cm, △ $d=0.115$ cm, $D=4.9$ cm, + $d=0.115$ cm, $D=7.3$ cm, ○ $d=0.115$ cm, $D=9.9$ cm, ■ $d=0.210$, 0.325, and 0.435 cm, $D=3.4$, 4.9, 7.3 and 9.9 cm.

when $Q < 4$ cm^3/s. At higher gas flow rates single bubbles are formed in both cases. Figure 1 indicates that for the 0.115 cm orifice the number of bubbles in each group increases with chamber diameter. This is expected because at high ratios of chamber to nozzle diameter, D/d, the chamber pressure would drop much less after each bubble detachment than at lower ratios where the gas movement inside the chamber is slower due to wall effect. This makes the bubble detachment at high D/d an unstable process producing many bubbles in rapid succession each time. A confirmation of this is the observation of irregular formation frequencies in the case of 9.9 cm chamber and 0.115 cm orifice (Table 1). Experiments conducted in this work show that in the region where grouped bubbles are formed the effect of chamber diameter becomes significant in the region of $D/d \geqslant 30$. In comparison, Hayes *et al.*[2] found no effect of chamber diameter in their experiments conducted in the range $4.5 \leqslant D/d < 33$. The behaviour of the three largest orifices in the region of flow rates $Q < 4$ cm^3/s almost coincides. The group bubble formation starts at chamber volume equal to 1620 cm^3 and the number of grouped bubbles formed using these three chambers is practically independent of the chamber diameter (Figure 1).

Table 1 shows the bubble formation frequency for two chamber volumes at various gas flow rates when the 9.9 cm diameter chamber is used. It should be noted that the frequencies in this Table refer either to single bubble formation or to group formation. Table 1 shows that for a given flow rate in the region $Q \geqslant 8$ cm^3/s the formation frequency decreases as the orifice diameter increases. This is expected because larger orifice diameters produce larger bubbles. In addition, it is observed that increasing the chamber volume results in a decrease of frequency due to the formation of larger bubbles, as will be explained later. Contrary to this, Table 1 shows that in the region of flow rate $Q \leqslant 3.9$ cm^3/s, while there is always a decrease of frequency with the chamber volume, there is not a unique effect of nozzle diameter on it. The last is apparently a result of group formation. The increase of gas flow rate results in an increase of frequency in both regions, as expected. It should be noted at this point that increasing the gas flow rate from 3.9 to 8 cm^3/s results in a relatively large increase of frequency, because of changing the mode from group to single bubble formation. A region of constant frequency has not been observed within the experimental range studied here.

Figures 2 and 3 show that the individual bubble volume continuously increases with gas flow rate. A discontinuity is noticed for some nozzles near flow rate $Q = 4$ cm^3/s. Another observation is that, with the exception in the range $Q \leqslant 4$, the bubble size increases with the nozzle diameter. Similar phenomena are also observed in the other experiments (not shown here) conducted with the rest of cylinder diameters and volumes. The previously described 'anomalous' behavior in the region $Q \leqslant 4$ cm^3 is due to the group bubble formation. Figures 2 and 3 indicate that the bubble volume increases almost linearly with the flow rate for $Q \geqslant 4$ cm^3/s, something observed also by other workers[1,2,8].

Figure 4 shows that the bubble volume continuously increases with the chamber volume until a critical chamber volume, $V_{c,cr}$, is reached above which it becomes

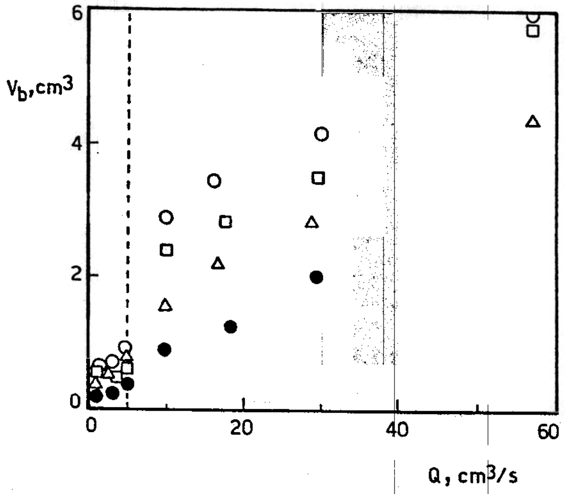

Figure 2. Mean volume of individual bubbles vs. gas flow rate for various orifices. $D = 9.9$ cm, $V_c = 8665$ cm^3. ● $d = 0.115$ cm, △ $d = 0.210$ cm, □ $d = 0.325$ cm, ○ $d = 0.435$ cm.

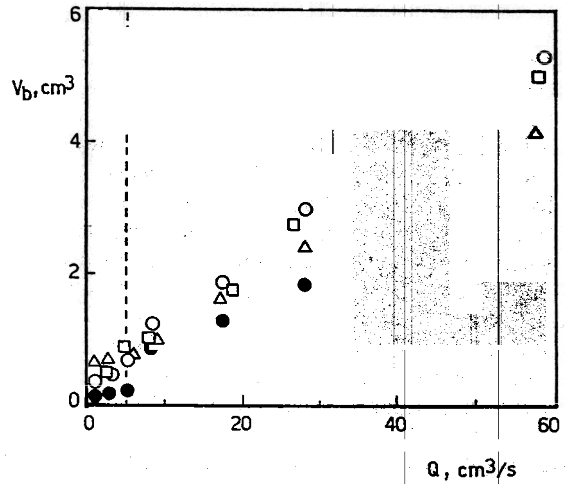

Figure 3. Mean volume of individual bubbles vs. gas flow rate for various orifices. $D = 9.9$ cm, $V_c = 600$ cm^3. ● $d = 0.115$ cm, △ $d = 0.210$ cm, □ $d = 0.325$ cm, ○ $d = 0.435$ cm.

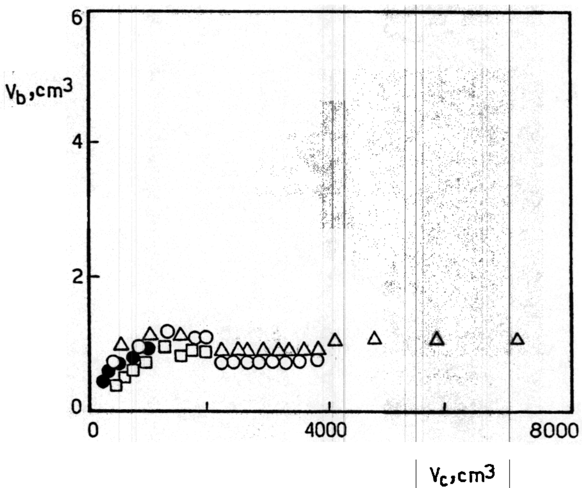

Figure 4. Mean volume of individual bubbles vs. chamber volume for various chamber diameters. $d = 0.325$ cm, $Q = 3.87$ cm^3/s. ● $D = 3.4$ cm, ○ $D = 4.94$ cm, □ $D = 7.3$ cm, △ $D = 9.9$ cm.

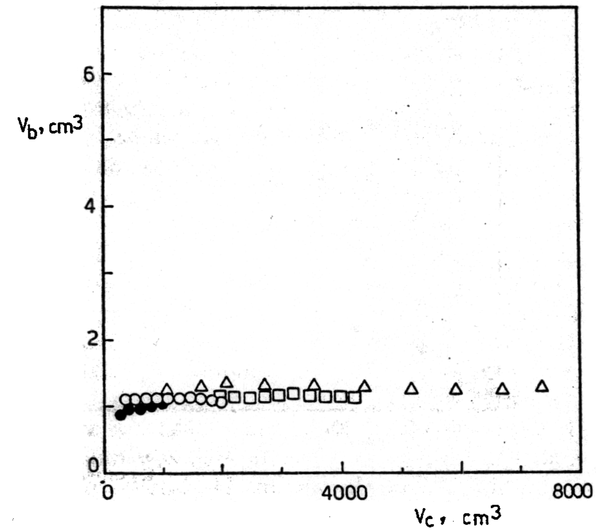

Figure 5. Mean volume of individual bubbles vs. chamber volume for various chamber diameters. $d=0.115$ cm, $Q=16.1$ cm^3/s. ● $D=3.4$ cm, ○ $D=4.94$ cm, □ $D=7.3$ cm, △ $D=9.9$ cm.

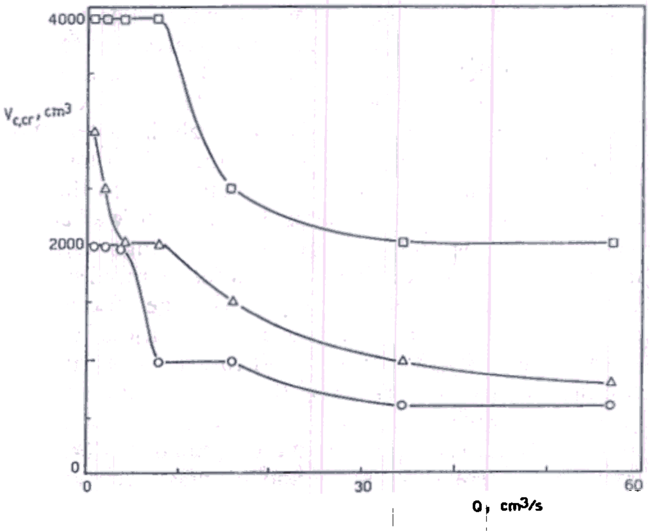

Figure 7. Experimental critical chamber volume above which there is no effect on bubble volume vs. gas flow rate. ○ $d=0.210$ cm, △ $d=0.325$ cm, □ $d=0.435$ cm.

independent of chamber volume. The reaching of a constant V_b is thought to be a result of almost constant chamber pressure (very small pressure fluctuations) existing at large chamber volumes. Figure 5 shows that $V_{c,cr}$ becomes smaller as the nozzle diameter decreases and the gas flow rate increases. The last is apparently due to the increase of chamber pressure with the increase of Q and the decrease of d. Davidson and Amick[1] also observed that the $V_{c,cr}$ decreases as Q increases and d decreases. Figure 5 shows the experimental results for the 0.115 cm orifice and $Q=16.1$ cm^3/s. No noticeable effect of V_c on V_b is observed here. Similar behaviour is seen with the rest of the experimental results (not shown here) for the 0.115 cm orifice at still higher flow rates. In the region where single bubbles are formed, it was observed that the effect of D on V_b is very small with a slight tendency to produce greater bubbles with the increase of D. This is true for all orifices studied. Contrary to this, a greater effect of V_c on V_b is observed in the region where grouped bubbles are formed. Thus, Figure 6 shows no effect of V_c on V_b for chamber diameters 3.4 and 4.9 cm where single bubbles are formed ($Q<2$ cm^3/s) and a small effect for chamber diameters 7.3 and 9.9 cm where group bubbles are formed ($Q<4$ cm^3/s). Figure 7 summarizes the experimental results for $V_{c,cr}$ at various Q and d. For comparison, Hayes *et al.*[2] found that for a 0.316 cm orifice and $Q=2.6$–40 cm^3/s the $V_{c,cr}$ is about 800 cm^3. Kupferberg and Jameson[6] for a 0.317 cm orifice and $Q=5$–33.3 cm^3/s, found a critical chamber value of about 1500 cm^3. Park *et al.*[11] found that for $d=0.33$ cm and $Q=0.055$ cm^3/s, $V_{c,cr}$ would be around 5000 cm^3.

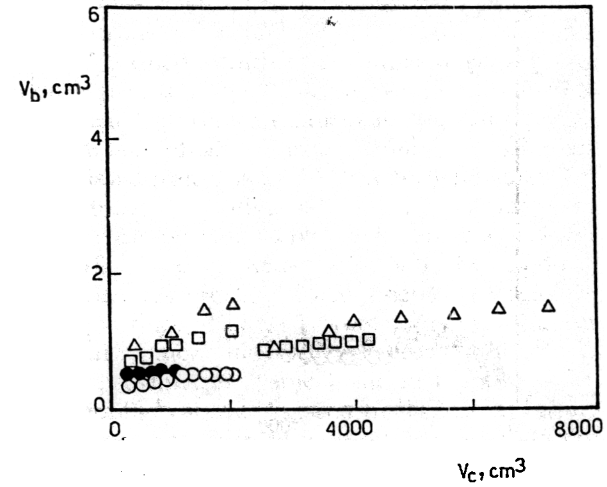

Figure 6. Mean volume of individual bubbles vs. chamber volume for various chamber diameters. $d=0.115$ cm, $Q=3.87$ cm^3/s. ● $D=3.4$ cm, ○ $D=4.94$ cm, □ $D=7.3$ cm, △ $D=9.9$ cm.

Weeping

Observations in the present work show that weeping never occurred when using the two smallest orifices for all flow rates studied here. Weeping in the 0.325 cm orifice occurs in the region of chamber volumes $V_c<1000$ cm^3 and gas flow rates $Q<16$ cm^3/s while for the 0.435 cm orifice it occurs mainly in the region $V_c<5000$ cm^3 and $Q<29$ cm^3/s. The minimum flow rates obtained in this work to stop weeping are smaller than the ones predicted by the model developed by Kupferberg and Jameson[7].

CONCLUSIONS

The experimental results of this work show that besides chamber volume the chamber diameter can also play a significant role in bubble formation. It was found that for the 0.115 cm orifice the number of grouped bubbles ($Q\leqslant 4$ cm^3/s) increased with chamber volume and chamber diameter. For the rest of the orifices, the effect of chamber diameter is insignificant. In general, in the experimental range of $D/d<30$ the effect of chamber diameter is insignificant. At higher ratios the influence becomes important. The bubble formation frequency decreases with the increase of orifice diameter and chamber volume.

No weeping occurred for $d=0.115$ and 0.21 cm.

Weeping at the two largest diameters is observed at low flow rates and moderately low chamber volumes.

NOTATION

A_o	area of orifice, cm^2
c	velocity of sound in the gas, cm/s
d	orifice diameter, cm
D	chamber diameter, cm
g	gravitational acceleration, cm/s^2
N_c	capacity number (defined in equation (1)), dimensionless
N_b	number of bubbles per group (burst)
Q	gas flow rate, cm^3/s
V_b	individual bubble volume, cm^3
V_c	chamber volume, cm^3
ρ_g	gas density, g/cm^3
ρ_l	liquid density, g/cm^3

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