Article
Effect of Sparger Characteristics on Bubble-Formation Dynamics under Oscillatory Air Pattern

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Abstract: The size of bubbles generated from a porous sparger is at least an order of magnitude larger than the pore diameter under the steady air pattern. Recent studies have shown that the bubble size can be significantly reduced when the steady air flow is replaced by an oscillatory pattern. However, the effectiveness of oscillatory air flow on reducing bubble size under different sparger characteristics is yet to be studied. This work fundamentally investigates the response of bubble size to sparger characteristics under an oscillatory air pattern by segregating the bubble formation subprocesses into bubble detachment and consequent coalescence. The results show that bubble size significantly decreased with hydrophilic plates regardless of contact angle, owing to depressed coalescence, while no impact was observed for a hydrophobic plate. The influence of the oscillatory air pattern on decreasing bubble size was weakened as the chamber volume was increased, and above a critical volume the bubble-formation process became similar with that under a steady air pattern. An optimum plate thickness was obtained for bubble generation by avoiding weeping, and meanwhile taking full advantage of the momentum force by the oscillatory airflow. The outcomes show that the oscillatory air pattern in determining bubble formation closely depends on the sparger characteristics, which should be appropriately determined.

Keywords: bubble size; sparger configuration; oscillatory air pattern; coalescence

1. Introduction

Microbubbles have been involved in many different physical and chemical industrial applications, including chemical mixing, froth flotation and the petrochemical industry [1–5]. Bubble size is of great importance since it determines the contact surface area for mass and heat transfer and thus influences process efficiency [6,7].

In industrial applications where two-phase flow is of great importance, spargers are usually used to produce and disperse bubbles efficiently in multiphase reactors or contacting devices. Different types of spargers have been designed, including ring-type distributors, perforated plates, porous membranes, and multiple-arm spargers [1,8–10], among which plate spargers with porous materials are often used owing to the simplicity of construction, reasonable price and high efficiency [11]. However, bubbles are usually formed at a size that is an order of ten times or more larger than the orifice diameter with a steady air pattern, which greatly hinders its industrial application. Recent studies have shown that changing air pattern from steady-state to oscillatory-state could be a cost-effective method for producing microbubbles [12,13]. Oscillatory air patterns lead to small bubbles by driving the bubbles breaking off from the orifice plate at an earlier stage and depressing bubble coalescence after the first bubble is detached from the orifice [12,14,15].

Bubble size for a porous plate is also determined by the sparger geometry [16,17]. In general, bubble size under a steady air pattern is closely related to the sparger geometrical
characteristics, such as pore size [18,19], plate thickness [20], plate wettability condition [21] and chamber volume [22]. A preliminary study has been conducted to investigate the configuration influence of a multiorifice sparger on bubble size under an oscillatory air pattern. The sparger geometrical characteristics investigated included chamber volume, orifice size and plate thickness [23]. It was reported that the bubble size was positively correlated with the chamber volume and the orifice size, but a nonlinear relationship was observed between the bubble size and the plate thickness. However, the mechanism for the dependence of bubble-formation dynamics on sparger geometry under an oscillatory air pattern was not discussed.

Bubble formation from an orifice is ultimately determined by two subprocesses, including bubble detachment and coalescence. The present work aims to describe in detail the bubble-formation dynamics under an oscillatory air pattern by varying the sparger geometry. After careful consideration of which parameters affect the bubble-formation dynamics, three parameters were chosen for study: plate wettability, chamber volume and plate thickness. The underlying mechanisms for the change of bubble-formation subprocesses were also discussed. It is believed that the outcomes of this work could facilitate bubble generation when bubble size is crucial for determining process efficiency.

2. Experimental Setup and Methods
2.1. Materials and Experimental Setup

Methyl isobutyl methanol (Aladdin, Shanghai, China) was used as a frother. Deionized water was used throughout the work. The porous plates were purchased from the Ruipu metal material, China. The plate thickness was measured using a micrometer with a standard error of 0.01 mm. Anhydrous ethanol and acetone (Tianjin Damao Chemical Reagent Factory, Tianjin, China) were ultrasonically used to clean stainless-steel plate surfaces. Sulfuric acid, stearic acid, potassium permanganate and potassium dichromate (Sinopharm Chemical Reagent Co., Ltd., Shanghai, China) were used to modify the plate wettability. The static contact angle for each plate was measured using the sessile drop method.

The porous sparger is shown in Figure 1. The subprocesses of bubble formation were observed through the transparent box made of acrylic material and the box dimension was as follows: length 10 cm, height 15 cm and width 3 cm. The observation box was divided into three sections: the two side chambers and the middle part. A single-orifice stainless-steel plate (length of 2 cm) with a pore diameter of 60 µm was placed in the middle part to observe the formation of bubbles. The two side chambers were equipped with porous stainless-steel plates with the same pore size. The side chambers were designed to divert some airflow from the middle plate to avoid jetting flow during bubble formation. An air chamber with a length of 9.5 cm and a width of 2.5 cm was positioned below the porous plate. The height of the air chamber can be adjusted to vary its volume. Oscillatory air supplies were provided by a high-frequency solenoid valve (MHE2, Festo, Esslingen, Germany). Air was introduced to the sparger when the valve was on and was cut off when the solenoid valve was off. A high-speed dynamic system (FASTCAM MINI UX, Tokyo, Japan), used to capture bubble-formation microprocess, was placed vertically in the middle of the observation chamber at a distance of 300 mm. The illuminated equipment was a halogen lamp. The obtained images of bubbles were processed and analyzed using the image-processing software ImageJ. Bubble size was characterized by the Sauter mean bubble diameter.

The monitoring device for air pressure consisted of three parts: a pitot tube (Dwyer Instruments, Michigan City, IN, USA) was used to transfer the air into the pressure transducer. A pressure transducer supplied by Conasen in China was used to measure the air-pressure change and a data-acquisition device produced by Heng kai in China was used to record and present the pressure change in the digital form of different voltage valves. The wettability (i.e., contact angle) of the plate surface was measured using a contact-angle measurement instrument (Biolin Scientific, Gothenburg, Sweden).
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Figure 1. A schematic of the experimental setup.

2.2. Experimental Procedure

The MIBC solution with a concentration of 50 ppm was added to the observation chamber to reach the liquid height of 5 cm. Note that the MIBC concentration exceeded its critical coalescence concentration to reduce the occurrence of bubble coalescence after formation [24]. The liquid level was maintained the same for the three parts of the viewing chamber to reduce the experimental deviation of bubble formation caused by the hydraulic-pressure differentiation. Then, the oscillatory frequency and on/off time ratio were set at 60 Hz and 0.2, respectively. The airflow volume and gas pressure were kept at 1.5 L·min$^{-1}$ and 0.2 MPa, separately. When the experimental device reached a steady status, the high-speed camera began capturing the bubble formation microprocesses at a shooting speed of 4000 fps. The sparger with the required plate wettability and thickness was placed in position before air was supplied, and the chamber volume was adjusted as required.

The measured voltage signals by the pressure transmitter were converted to the air-pressure values. The conversion of voltage to pressure can be seen elsewhere [12]. The relationship of voltage value and air pressure was as follows:

$$U = 7.23 \ P \quad (1)$$

where $U$ is the symbol of the voltage valve (V); $P$ is the symbol of air pressure (MPa).

3. Results and Discussion

To fully study the influence of sparger configuration on bubble generation, the bubble-forming dynamics from an orifice were divided into two parts: the bubble detaching from the orifice, as well as the bubble coalescence between the leading and the successive bubbles after detachment. The characteristics of each part with different sparger configurations under an oscillatory air pattern were studied.

3.1. Plate Surface Wettability

To study the effect of surface wettability on bubble formation, a plate was selected with an orifice size of 60 µm and a thickness of 0.05 mm. The chamber volume was set at 5 mL. Figure 2 shows the spreading of a water drop on the plates with different wettability. The wettability was characterized by the contact angle. The plate hydrophobicity increased over the contact angle. As shown in Figure 2, the surface wettability varied from super-hydrophilic to hydrophobic with contact angles of 3.58°, 49.44°, 75.66° and 116.52°, respectively.
To study the effect of surface wettability on bubble formation, a plate was selected for the bubble formation under an oscillatory air state. The first bubble detached from the orifice with a low velocity and the successive bubbles could catch up and coalesce with it. The results show that a hydrophilic plate needs to be selected for the bubble formation under an oscillatory air state.

Figure 3b shows the bubble size of the first and final bubbles with the increase in contact angle under an oscillatory air pattern. The bubble-formation process under a steady air pattern is plotted in Figure 3a for comparison. Figure 3b reveals that switching air patterns from a steady state to an oscillatory state could significantly decrease bubble size, but the plate wettability exhibited little impact on bubble formation when the contact angle was less than 90°. More specifically, the size of the first bubble increased from 658 µm at 3.58° to 673 µm at 75.66° (an increase of only 2.28%) under a steady air state and remained constant under the oscillatory air state. The final bubble size increased by 10.43% for the steady air pattern, while it increased by only 3.71% under the oscillatory air pattern. The number of coalesced bubbles increased from 19 to 22 (a 15.79% increase) under a steady air pattern, while it remained constant under an oscillatory air pattern. Differently, the hydrophobic plate surface exhibited a different effect on bubble formation. According to Figure 3, bubble coalescence was completely depressed when the contact angle increased to 116.51°, regardless of the air pattern. The size of the first bubble sharply increased to 3851 µm and 3824 µm for steady and oscillatory air states, respectively. The result implies that oscillatory air patterns cannot effectively decrease bubble size when hydrophobic media is used for bubble formation.

To further study the influence of plate wettability on bubble formation under an oscillatory air state, Figure 4 presents the contact rims of bubbles at the hydrophilic and hydrophobic plate surfaces, respectively. The diameter of the contact rim was equal to the orifice diameter for the hydrophilic surface, while it was much larger than that for the hydrophobic surface. It is expected that the reinforced momentum force caused by the oscillatory air pattern would overwhelm the adhesive force resulting from the plate for the hydrophilic surface and drive bubbles to detach with a high velocity. The first bubble would have ascended away when the successive bubbles were formed and thus eliminate bubble coalescence. In contrast, the momentum force was offset by the increased adhesive force resulting from the enlarged contact rim for the hydrophobic surface [21,25]. Therefore, the first bubble detached from the orifice with a low velocity and the successive bubbles could catch up and coalesce with it. The results show that a hydrophilic plate needs to be selected for the bubble formation under an oscillatory air state.
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(a) (b)

Figure 3. The bubble size and number of coalesced trailing bubbles under steady air pattern (a) and oscillatory air pattern (b).

3.2. Chamber Volume

Figure 5 shows the influence of the chamber volume on the bubble size and the number of coalesced trailing bubbles under different air patterns. The orifice diameter was set at 60 μm and the plate thickness remained at 0.05 mm. The air-chamber volume was varied at 5 mL, 12 mL, 33 mL, 55 mL, 142 mL, 470 mL and 492 mL, respectively. Again, the bubble-formation process as a function of chamber volume under a steady air state is also presented in Figure 5a for comparison.

Figure 5b reveals that the chamber volume exhibited a significant effect on bubble formation under an oscillatory air pattern. The first bubble size increased from 579 μm to 688 μm (an 18.8% increase) as the chamber volume was enlarged from 5 mL to 492 mL. Differently, the first bubble size was much bigger but experienced a small increase from 673 μm to 698 μm (i.e., a 3.7% increase) under a steady air state, as shown in Figure 5a. In contrast, the final bubble size increased from 933 μm to 1725 μm (an 84.9% increase) over increasing chamber volume under an oscillatory air pattern, while it increased from 1472 μm to 1618 μm (i.e., a 9.9% increase) under a steady air pattern. Similarly, it was observed that the increase in the number of coalesced trailing bubbles fell in the same trend with the final bubble size. The number of coalesced trailing bubbles increased from 4 for the chamber volume of 5 mL to 22 for the chamber volume of 492 mL (i.e., 4.5 times) under

Figure 4. Comparison of contact rims of bubbles for a hydrophilic surface (contact angle: 3.58°) and a hydrophobic surface (contact angle: 116.52°).
the oscillatory air pattern, showing that the bubble coalescence was the main cause for
the increased bubble diameter. Note that the difference in bubble size between oscillatory
and steady air supplies progressively decreased when the chamber volume increased to
470 mL, above which no difference was observed. The result indicates that the effect of the
oscillatory air pattern on decreasing bubble size weakens as the chamber volume increases.
Above a critical volume, the oscillatory air state functions similar to the steady air state in
determining bubble size.

\[ Nc = \frac{4g\rho g Vc}{\pi d_0^2 Pc} \]  \hspace{1cm} (2)

where \( \rho \) is the symbol of the air density \( (\text{kg} \cdot \text{m}^{-3}) \), \( Vc \) is the symbol of the air chamber
volume \( (L) \), \( d_0 \) is the symbol of the diameter of an orifice \( (m) \), \( g \) is the symbol of the
gravity acceleration \( (\text{m} \cdot \text{s}^{-2}) \) and \( Pc \) is the symbol of the air-supplied gage pressure to the
chamber \( (\text{MPa}) \).

It was calculated that under the current configuration, the critical chamber volume for
a constant flow condition was 44.67 mL. The pressure became constant when the chamber
volume was above 446.7 mL. In a volume within this range existed an intermediate flow
status. For the constant flow condition in a small chamber, the flow status of gas exiting the
air chamber (i.e., introduced into a bubble) is the same as that of air introduced into the air
chamber. As shown in Figure 6a, air pressure at the orifice exit varied simultaneously over
the air pattern and the peak pressure was far greater than that under a steady air pattern.
Hence, the extra lifting force generated by the oscillatory airflow drove bubbles to detach
from the orifice exit at an earlier stage. More importantly, the intensified momentum force
pushed bubbles to detach with a high velocity. The high rising velocity eliminated the
successive bubbles to catch up and coalesce; for the intermediate condition, the flow pattern
of air exiting the chamber did not necessarily become synchronous to that of air introduced
into the chamber; further enlarging the chamber would reach a constant pressure condition
(as shown in Figure 6b). The large chamber imposed a cushioning effect on the airflow
pattern and the pressure at the orifice exit became constant, which coincided with that
under a steady air state. Therefore, the detached bubble had a low velocity due to the
weakened momentum force because of the bigger air chamber. The low rising velocity

Figure 5. Effects of chamber volume on bubble formation under steady air pattern (a) and oscillatory
air pattern (b).
enabled the successive bubbles to catch up and coalesce, which resulted in a bigger final bubble size.

Figure 6. Air pressure at the orifice outlet for different chamber volumes with steady (a) and oscillatory (b) air patterns.

In summary, the chamber volume could impose a significant impact on bubble formation by affecting the airflow pattern at the orifice outlet. Under an oscillatory air pattern, the air pressure varies with a periodic fluctuation [27] and its amplitude declines with the increase in gas chamber volume, which dramatically influences bubble detachment and coalescence. Therefore, to take advantage of the increased momentum force originating from the oscillatory air pattern, it is necessary to maintain the small chamber volume when microbubbles are required.

3.3. Plate Thickness

The effect of plate thickness on the process of bubble formation is presented in Figure 7. In these tests, the plate thickness was set at 0.01 mm, 0.05 mm, 0.1 mm and 0.2 mm, respectively. The orifice size was 60 μm, the chamber volume was maintained at 5 mL, and the oscillatory frequency and on/off time ratio were kept at 60 Hz and 0.2, respectively.

Figure 7. Effects of plate thickness on bubble size and number of coalesced trailing bubbles under oscillatory air pattern.
As shown in Figure 7, the size of the first bubble experienced little difference over increasing the plate thickness, varying from 699 \( \mu m \) at a thickness of 0.01 mm to 656 \( \mu m \) at a thickness of 0.2 mm (a decrease of 6.15%). A nonlinear correlation existed between the final bubble size and the plate thickness. The smallest final bubble size was 927 \( \mu m \) obtained at a plate thickness of 0.05 mm. Note that the number of coalesced trailing bubbles shows the same trend as the final bubble size, indicating that the plate thickness mainly influenced the bubble coalescence.

Figure 8 schematically shows the effect of plate thickness on the weeping under an oscillatory air pattern. For a thinner plate (e.g., 0.01 mm), the weeping phenomenon could appear when the airflow was shut down as the channel resistance is weak and could not hold the hydraulic pressure in the channel. The weeping liquid can lead to severe plugging in orifices [28], and a larger lifting force is needed in order to overcome the capillary pressure of the liquid column in the channel (see Figure 8a). Hence, the momentum force is dissipated and bubbles detach from the orifice at a low velocity. The successive bubble can reach and coalesce with the former, resulting in a bigger bubble size. As shown in Figure 8b, the capillary resistance increases as the plate thickness increases, which retards the downward liquid flow inside the orifice channel and avoids the occurrence of the weeping phenomenon [29]. Meanwhile, the increased capillary resistance can also weaken the lifting force resulting from the oscillatory air pattern. Similarly, bubbles detach at a low velocity, which causes more bubble coalescence. Therefore, an orifice plate of appropriate thickness should be selected to avoid the weeping while minimizing the energy dissipation of the oscillatory air pattern imposed by the channel resistance.

![Figure 8. Schematic diagram of the effect of plate thickness on liquid movement when shutting off air supply.](image-url)

**4. Conclusions**

In the present work, the effect of sparger characteristics on bubble formation under an oscillatory air pattern was investigated, including the wetting condition, chamber volume and plate thickness. The main outcomes are given below:

- An oscillatory air pattern could significantly decrease bubble size when a hydrophilic plate was used. However, its influence on bubble formation was offset by the increased restraining force resulting from the enlarged contact rim of bubbles with the plate when a hydrophobic surface was applied.

- Bubble size and the number of coalesced trailing bubbles were positively related to the chamber volume under an oscillatory air state. A small chamber volume was
preferred to maintain a constant flow condition to fully use the enhanced momentum force for bubble detachment.

- A nonlinear relationship existed between the plate thickness and the bubble size. An appropriate thickness could not only avoid the weeping phenomenon but also reduce energy dissipation caused by capillary resistance. Therefore, the suitable plate thickness should be selected under an oscillatory air pattern.

The outcomes of this study revealed that the sparger characteristics could impose significant effects on the bubble-formation dynamics under oscillatory air supply. The sparger geometry should be properly designed to obtain the desired bubble size under oscillatory air supply.

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