Effect of Orifice Shape and Dissolved Gas on Bubble Generation in Two-Phase Nozzle Flow by Pressurized Dissolution Method

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Abstract: The aim of the study is to examine the effect of the amount of the dissolved gas on the two phase flow and to examine the acceleration of bubble generation on two-phase nozzle flow by modifying the shape of orifice plate. In the experiment, the molar concentration of CO₂ gas was changed at the dissolution process. As increasing the CO₂ molar concentration, the void fraction increased and the liquid velocity decreased at the throat. On the other hand, the bubble velocity was almost constant when dissolved gas rate was changed. Therefore, the slip velocity between the bubble and the liquid increased. Moreover, the amount of bubble is different by changing the hole type of orifice plate such as different holes diameter and respective cross section area for each plate. In case of the orifice of seven holes, it cannot reach the sound speed at the throat but it is closest to the sound speed in the case of other orifices.

Keywords: Two-phase Nozzle Flow, Pressurized Dissolution Method, Void Fraction, Bubble Velocity, Slip Velocity

1. Introduction

Nozzle is a device that converts the enthalpy of the fluid into kinetic energy. It is used in two-phase flow ejector and liquid metal MHD generator [1]. The variation of the flow acceleration in two-phase flow nozzle causes the slip velocity because of different property of density between gas and liquid.

This is the problem of energy loss due to the slip velocity in industrial application such as an acceleration nozzle in a liquid metal MHD generation system. Analyzing the micro-bubble two-phase flow in the acceleration nozzle is important to reduce the energy loss.

A lot of study investigates on the micro-bubble two-phase flow and the interest for their application also increases on various engineering field. Micro-bubble has small slip velocity between the bubble and the liquid around it. The gas-liquid two-phase flow with micro-bubble generation applies in the supersonic nozzle to reduce the slip velocity.

The nozzle consists of a converging section and a diverging section. When the velocity of a fluid reaches the sound speed at the throat, the supersonic flows appear in the diverging section. Because the sound speed of the gas-liquid two-phase flow is very low compared to the sound speed of liquid (about 1500 m/s) and the sound speed of gas (about 340 m/s under the atmospheric pressure), it is easy to obtain the supersonic flow by using the gas-liquid two-phase fluid. In the case, it is important for the velocity of the fluid to reach the sound speed at the throat.

The pressurized dissolution is a method of micro-bubble generation by reducing the pressure of the water after the water had been saturated with gas under a high pressure [2]. After adding the carbon dioxide and the water into a tank, it was pressurized in the tank. When the pressure was decreased, micro-bubbles were generated in the water in this study. The procedure of the pressurized dissolution and the experimental conditions are represented in the previous paper [3].

In the previous work, it was studied that pressurized dissolution method in the converging-diverging nozzle or the supersonic nozzle by micro-bubble generation method because the pressurized dissolution method is one of the micro-bubble generation methods. However, the previous study could not perform supersonic flow at the nozzle by the pressurized dissolution method [4].

Therefore, the pressurized dissolution method was modified by using the orifice plate. The plate was mounted at the exit of an upper tank to reduce once the diameter of the flow channel. The pressure of the water flow was reduced at the orifice, and the micro-bubble was generated at the converging section of the nozzle. If the flow is gas-liquid two-phase flow at the throat, the sound velocity is very low and the flow becomes supersonic easily after the throat [4].

It is expected that the flow becomes supersonic by modified pressurized dissolution method. In the present study, the pressurized dissolution method was modified by four types orifice plate for the acceleration of micro-bubble. In addition the effect of the amount of the dissolving gas on the two-phase nozzle flow was investigated.

2. Experimental Apparatus

Figure 1 shows a blow-down type experimental apparatus, which consists of an upper tank, a lower tank, a nozzle of the test section between the tanks. An orifice is set at the nozzle inlet in order to generate micro-bubbles by the pressurized dissolution method. After making the pressure difference between the upper and the lower tanks, a high speed flow in the nozzle can be obtained by opening a valve downstream of the nozzle.

The upper and the lower tanks are cylindrical. Both tanks are 1000 mm of height and their inside diameter is 331 mm. The side wall of the upper tank is made of
transient acrylic to observe the fluid inside of the tank. The top and the bottom covers of the upper tank are made of PVC. The lower tank is also made of PVC.

Figure 2 shows the converging-diverging nozzle as the test section. The cross section of the nozzle is a circle. The nozzle is made of transparent acrylic to observe the flow in the nozzle. The pressure measurement taps mentioned as Nos.1 to No.7 in Fig.2 are set along the nozzle to measure the pressure.

In the converging nozzle, the flow is accelerated and the pressure decreases along the nozzle. The micro-bubbles are expected to be generated in the converging nozzle in the pressurized dissolution method. The previous work, however, showed the bubble generation in the converging nozzle was not enough to obtain the supersonic two-phase flow in the diverging nozzle [3]. Therefore, in order to promote the bubble generation, the orifice was set at the nozzle inlet, that is, before the throat.

Generally, the sound speed of a homogeneous gas-liquid two-phase flow is expressed as Eq. (1). Here, \( n \) is polytrophic index. In the rage of the void fraction of less than 0.5, the sound speed decreases as the void fraction increases. Therefore, the orifice is expected to help for the flow to reach its sound speed at the throat because the micro-bubbles are generated at the orifice by the pressurized dissolution method.

\[
\alpha = \frac{nP}{\alpha(1-\alpha)\rho L} 
\]  

(1)

3. Experiment

3.1 Experimental method

After a half of the upper tank was filled with water of about \( 43 \times 10^{-3} \) m\(^3\), the pressure in the upper tank was set to atmospheric pressure with N\(_2\) gas. After deaeration of the upper tank, the upper tank was pressurized by N\(_2\) and CO\(_2\) gases. The total pressure in the upper tank was fixed at 200 kPa but the partial pressure of CO\(_2\) gas changed as Table 1. The experimental condition was set in equilibrium state after mixing the water and the gases.

Because the solubility of N\(_2\) gas is very small comparing with that of the CO\(_2\) gas, the effect of CO\(_2\) gas was only considered in the pressurized dissolution method. The amount of the dissolving gas is proportional to the partial pressure of the gas. Therefore the amount of the dissolving gas was also changed as the CO\(_2\) molar concentration was changed shown in Table 1. The experimental condition Nos.1 to 8 represent for the modified pressurized dissolution method with an orifice plate. In experimental condition Nos.1 to 5, the orifice plate with one hole is used. In the experimental condition No.6, the 7 holes orifice plate was used, 19 holes orifice plate was used in the experimental condition No.7 and the orifice plate with mesh was used in the experimental condition No.8. The experimental condition No.9 represents the case without the orifice plate as the conventional pressurized dissolution. Four types of orifice plate are shown in Fig.3. All of the plates are aluminum plates of 140 mm length, 140 mm width and thickness 1 mm. The diameter of the hole of plate is 20 mm for one hole of orifice plate 1. The orifice plate 2 has 7 holes of 7 mm diameter. The orifice plate 3 has 19 holes of 5 mm diameter. Orifice plate 4 has a hole of 40 mm diameter covered by a mesh (mesh number 16, wire diameter: 0.4 mm).

The pressure in the lower tank was set to atmospheric pressure. After the experimental condition was set, the experiment was began by opening the valve downstream of the nozzle.

3.2 Pressure measurement

The pressures in the upper tank and the lower tank were measured by a silicon diaphragm pressure gauge which is attached to the top plate of each tank. The pressure distribution along the nozzle was measured by a semiconductor pressure transducer which was attached in the pressure tap Nos.1 to No.7 is shown in Fig.2. The pressure signal from the pressure gauge and the pressure transducer were recorded at intervals of 500 \( \mu \)s for 60 s.
In the experimental condition No.6, more micro-bubbles were generated than those in the experimental condition Nos.5, 7 and 8. There was no micro-bubble formation in experimental condition No.9 at the throat and converging section and it was just only single phase flow.

### 4.2 Pressure distribution along the nozzle

Figure 5 shows the time averaged pressure distribution along the diverging part of the nozzle. The pressure at each pressure tap was averaged in the quasi-steady state (5 s to 15 s after starting the experiment) [3][4]. The pressure increased along the nozzle. Because the pressure recovered in the diverging nozzle, the flow seemed subsonic in all experimental conditions.

### 4.3 Void fraction in a cross section

Void fraction was calculated by the ratio of the total area of micro-bubble at the throat to the cross-sectional area of the throat shown Eq. (2). The total area of micro-bubble was calculated by using the flow images taken with digital high speed camera. The cross-section of a bubble was assumed to be a circle as shown in Fig.6. The average void fraction was obtained for the 20 consecutive images in each experimental condition.

\[
\text{Void fraction} = \frac{\sum \text{Area} \text{of micro-bubble}}{\text{Cross-sectional area of the throat}}
\]

The void fractions for all experimental conditions were shown in Figs.7 and 8. The error bar showed 95% confidence interval. Comparing with Nos.1 to 5 in Fig.7, the void fraction increased with the CO₂ molar concentration. Further, the equivalent bubble diameter of the bubbles and the number of bubbles passing the throat for a second were obtained. In Fig.9, the left axis of ordinate denotes the equivalent bubble diameter at the

#### Table 1 Experimental conditions

<table>
<thead>
<tr>
<th>Experimental condition</th>
<th>Water temperature [°C]</th>
<th>Orifice plate No.</th>
<th>The partial pressure of CO₂ [kPa]</th>
<th>CO₂ molar concentration *10⁻³ [mol/L]</th>
<th>Upper tank absolute pressure [kPa]</th>
<th>Lower tank absolute pressure [kPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.1</td>
<td>16.9</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td>No.2</td>
<td>19.0</td>
<td>50</td>
<td>0</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No.3</td>
<td>19.0</td>
<td>100</td>
<td>0</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No.4</td>
<td>16.5</td>
<td>150</td>
<td>0</td>
<td>65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No.5</td>
<td>16.5</td>
<td>200</td>
<td>0</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No.6</td>
<td>12.7</td>
<td>2</td>
<td>200</td>
<td>87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No.7</td>
<td>13.0</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No.8</td>
<td>14.1</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No.9</td>
<td>18.9</td>
<td>Without orifice plate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

When the CO₂ molar concentration increased, the generation of bubbles was also increased in the experimental condition Nos.1 to 5. Therefore, the dark portion could be seen more in experimental condition No.5 rather than the experimental condition Nos.1 to 4.

In the experimental condition Nos.5 to 8 as shown in Fig.4 (5) to (8), micro-bubbles were observed from the converging section of the nozzle. In the experimental condition Nos.5 to 8, micro-bubble could be seen in three parts: throat, converging section and also diverging section.

#### 3.3 Flow rate measurement

The water level in the upper tank was recorded by a digital camera in order to obtain the flow rate. The height scale of 1 cm increments was set on the side wall of the upper tank. Based on the rate of change in the water level of 5 s to 15 s after starting the experiment, the flow rate was calculated. The accuracy of the flow rate is 1.1%.

#### 3.4 Flow image

The flow in the nozzle was taken by a high-speed camera with a back light system. In the study, bubbles were shown as dark because the bubbles blocked the back light.

### 4. Experiment Result

#### 4.1 Flow pattern

The flow pattern in the nozzle was taken by a high-speed camera. Figure 4 shows the flows over the entire nozzle and the close-up image at the throat. The image over the entire nozzle was taken at every 1 ms. The image at the throat was taken at every 0.1 ms to observe the flow in detail. The bubble generation depended on the CO₂ molar concentration was shown in Fig.4 (1) to (5). The close-up images also show that the bubbles were stretched along the flow at the throat.

When the CO₂ molar concentration increased, the generation of bubbles was also increased in the experimental condition Nos.1 to 5. Therefore, the dark portion could be seen more in experimental condition No.5 rather than the experimental condition Nos.1 to 4.

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#### (1) No.1     (2) No.2     (3) No.3     (4) No.4    (5) No.5

#### (6) No.6        (7) No.7         (8) No.8         (9) No.9

Fig.4 Flow pattern
In the experimental condition No.6, more micro-bubbles were generated than those in the experimental condition Nos. 5, 7 and 8. There was no micro-bubble formation in experimental condition No.9 at the throat and converging section and it was just only single phase flow.

4.2 Pressure distribution along the nozzle
Figure 5 shows the time averaged pressure distribution along the diverging part of the nozzle. The pressure at each pressure tap was averaged in the quasi-steady state (5 s to 15 s after starting the experiment) [3][4]. The pressure increased along the nozzle. Because the pressure recovered in the diverging nozzle, the flow seemed subsonic in all experimental conditions.

\[
\alpha_n = \frac{\sum \pi d_i^2}{A}
\]

4.3 Void fraction in a cross section
Void fraction was calculated by the ratio of the total area of micro-bubble at the throat to the cross-sectional area of the throat shown Eq. (2). The total area of micro-bubble was calculated by using the flow images taken with digital high speed camera. The cross-section of a bubble was assumed to be a circle as shown in Fig.6. The average void fraction was obtained for the 20 consecutive images in each experimental condition.

The void fractions for all experimental conditions were shown in Figs.7 and 8. The error bar showed 95% confidence interval. Comparing with Nos.1 to 5 in Fig.7, the void fraction increased with the CO\textsubscript{2} molar concentration. Further, the equivalent bubble diameter of the bubbles and the number of bubbles passing the throat for a second were obtained. In Fig.9, the left axis of ordinate denotes the equivalent bubble diameter at the
throat and the right axis of ordinate, the number of bubbles passing the throat for a second. Even if the CO$_2$ molar concentration increased, the equivalent bubble diameter was almost constant. Inversely the number of bubbles increased with the CO$_2$ molar concentration. Therefore, when the CO$_2$ molar concentration increased, the void fraction in a cross section increased because the number of bubbles increased.

The amount of the void fraction in the experimental condition No.6 was larger than the others because of the generation of micro-bubble at the throat was more observed than the other experiments. Therefore, the shape of the orifice plate in experimental condition No.6 had more effect in the generation of micro-bubbles. Then the void fraction could not perform in the condition No.9 because the micro-bubble generation was not found at the throat.

There were total 118 bubbles in the experimental condition No.5. The total number of bubble was 162 and it caused more potential to form the supersonic flow in experimental condition No.6. In the experimental condition Nos.7 and 8, the total number of bubbles was only 45 and 19 bubbles. In this experiment, the value of void fraction increased with the number of generated micro-bubbles.

4.4 The flow velocity
The liquid velocity at the throat was also calculated by using the flow rate and the void fraction at the throat as shown in Eq. (3). A single bubble velocity was obtained as an averaged velocity by using three successive flow images at the throat. The bubble velocity in Fig.10 was calculated as the average of 50 bubbles in each experimental condition. Figure 10 shows that the bubble velocity was almost constant and the liquid velocity decreased with the CO$_2$ molar concentration. Therefore, as increasing the CO$_2$ molar concentration, the slip velocity between the bubble and the liquid increased. The reason why the liquid velocity decreased may be that the increase of pressure loss of two-phase flow due to the increase in the void fraction.

Furthermore, the adiabatic sound speed and the isothermal sound speed assuming a homogeneous two-phase flow was calculated by Eq. (4) and (5), respectively.

Figure 11 and 12 show the liquid velocity and the sound speeds calculated at the throat. In all experimental conditions, the liquid velocity was lower than the adiabatic and isothermal sound speeds. In the case of No.6, the liquid velocity closed to the sound speed. Therefore, the orifice plate No.2 is suitable for supersonic flow condition.

\[ u_L = \frac{Q_L}{(1-a)A} \]  
\[ a_{ad} = \sqrt{\frac{k P_{th}}{\frac{a(1-a)}{\rho_L}} P_{th}} \]  
\[ a_{iso} = \sqrt{\frac{P_{th}}{\frac{a(1-a)}{\rho_L}}} \]

Fig.10 Liquid and bubble velocities

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5. Conclusion
As increasing the CO$_2$ molar concentration, the void fraction increased and the liquid velocity decreased at the throat. The bubble velocity was almost constant. Therefore, the slip velocity between the bubble and the water increased. Based on the pressure distribution along the nozzle and the flow velocity at the throat, it did not reach the sound speed in all experimental conditions.
Much micro-bubble could be generated in experimental condition No.6 at the throat comparing with the other experimental conditions. The orifice in the experimental condition No.6 had 7 holes of 7 mm diameter. In this experimental condition, the formation of the number of bubbles at the throat was more than the other experimental conditions and the liquid velocity was lower. Because of the higher bubble formation and lower liquid velocity, the higher void fraction was observed in experimental condition No.6. In addition, it approached to the sound speed expressed by Eq. (1) at the throat because of its void fraction. Therefore, the experimental condition design (7 holes with the diameter of 7 mm) was the most potential for supersonic among the other experimental conditions.

**Nomenclature**

- $a$ sound speed [m/s]
- $a_{ad}$ adiabatic sound speed [m/s]
- $a_{iso}$ isothermal sound speed [m/s]
- $\rho_l$ density of liquid [kg/m$^3$]
- $P$ pressure [kPa]
- $P_{th}$ pressure of the throat [kPa]
- $\alpha$ void fraction [-]
- $d_i$ diameter of bubble [m]
- $k$ heat capacity ratio of the carbon dioxide gas [-]
- $Q_k$ flow rate [m$^3$/s]
- $u_l$ liquid velocity [m/s]
- $A$ area of the throat [m$^2$]

**References**


