Gas Injection from Slot Nozzles with Various Shapes in Water

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Results of experiments examining behaviour of gas bubbles detouching from slot nozzles of various shapes are presented. Gas was injected into water through the slot nozzles of 200 mm in length and 0.05, 0.1 mm in width. Four types of the slot nozzles were used: (a) flat nozzle, (b) mountain-shaped nozzle, (c) valley-shaped nozzle, (d) unilaterally inclined nozzle. They were made of Teflon which is poorly wetted by water. The bubble behavior is described by two parameters: bubble diameter formed at the slot nozzle and the number of bubble sources. It was found that the gas injection through the mountain-shaped nozzle produces the smallest bubble while the largest bubble is formed when the valley-shaped nozzle is used. Bubbles produced at the flat nozzle and unilaterally inclined nozzle were almost the same in size which is intermediate between the bubble sizes for the mountain-shaped and valley-shaped nozzles. Comparative experiments showed that, when gas is injected through a wetted slot nozzle, the bubble size is much smaller than that for the nonwetted slot nozzle of the same design (flat nozzle) at lower gas flow rates. For all experiments, the bubbles become smaller as the number of bubble sources increased.

KEY WORDS: gas injection; slot nozzle; bubble; dispersion; refining; steel making; cold model.

1. Introduction

In metal refining processes, gas injection into molten metal has been performed in order to enhance the mixing and the refining reactions. Generally, the gas is injected by using a porous plug, an orifice or a nozzle made of refractory which is poorly wetted by molten metal. As a result, the bubbles formed under the gas injection become large, which leads to a decrease in the area of gas-metal interface where refining reactions proceed. Thus, a further improvement in the efficiency of the gas injection requires development of new injection techniques.

Recently, Li et al.1,2) investigated the gas injection into water and methanol by using a slot nozzle made of stainless steel. They examined influences of the gas flow rate on the bubble size and the distance between bubble formation sites. Since the gas was injected from the slot nozzle wetted by the liquids and the gas flow rate was comparatively low, it makes some difficulties in applying the obtained results to molten metal systems. As a result, the bubbles formed under the gas injection become large, which leads to a decrease in the area of gas-metal interface where refining reactions proceed. Thus, a further improvement in the efficiency of the gas injection requires development of new injection techniques.

The present study aims at clarifying the behavior of bubbles forming at a slot nozzle by using a water model system and non-wetted slot nozzles of various shapes. The gas flow rate was changed over a wide range.

2. Experimental

Figure 1 presents a schematic illustration of the experimental apparatus. Two vessels made of transparent acrylic resin were used for the experiments. The sizes of the vessels are 400×400×500 mm and 970×600×970 mm. The vessel was filled with water to bath depths of 400 mm and 600 mm, respectively. The slot nozzle was installed at the vessel bottom. Injected gas was nitrogen, and its flow rate was adjusted by a mass flow controller in the range from $7 \times 10^{-3}$ to $5 \times 10^{-3}$ m$^3$/s.

Figure 2 shows configuration of the slot nozzles. It consists of two smooth Teflon plates of 15 mm in thickness. The contact angle between Teflon and water is $108^\circ$.4) A sheet of U-shaped Teflon film was put between the two Teflon plates to make the slot. The slot width, $w$, was 0.05 or 0.1 mm, and the length, $L$, was 200 mm. The gas chamber volume in the slot nozzle was $4.8 \times 10^{-3}$ m$^3$. Four slot nozzles of different shapes were used. In the present study,
type (a) has a flat upper surface, type (b) is a mountain shaped type with the vertical angle of 120 degrees, type (c) is a valley-shaped type with the included angle of 60 degrees and type (d) is an unilaterally inclined type with the inclination angle of 30 degrees. The length of the gas flow path within the slot nozzles (a), (b) and (d) was 25 mm which was much larger than the slot width, while that within the nozzle (c) was less than 25 mm. It is considered that a constant flow condition was maintained owing to the pressure drop across the slot of nozzles (a), (b) and (d). For comparison, some experiments were carried out by using a wetted slot nozzle of type (a) made of stainless steel. Slot nozzles of small length of 10 mm (type (b) and type (c)) were also used, for which only one bubble source was observed.

To measure the bubble size and the number of bubble sources along the slot, the bubble formation was recorded by a high speed video camera (240 frame/s) and a still frame camera. For determination of the bubble size, the bubbles were considered as ellipsoidal with major and minor axes \( a_i \) and \( b_i \). The average bubble volume, \( V_B \), was calculated based on,

\[
V_B = \frac{4\pi}{3} \sum_i a_i^2 b_i / n \quad \text{(1)}
\]

where \( n \) is the number of bubbles. The mean size of equivalent spherical bubbles, \( d_B \), was obtained by the following equation.

\[
d_B = \left( \frac{6V_B}{\pi} \right)^{1/3} \quad \text{(2)}
\]

3. Results and Discussion

3.1. Bubble Formation Behavior

Three typical photographs of the bubble formation at the slot nozzle of type(a) (Teflon) are shown in Fig. 3. Figure 4 presents a schematic illustration of the bubble generation at the slot nozzle. Gas bubbles are formed along the slot at places spaced a certain distance and named as bubble sources. The bubble sources are not much moved along the slot during gas injection. Depending upon the gas flow rate, the bubble formation follows two distinct regimes, I and II as shown in Fig. 4. The bubble size increased with increasing gas flow rate. The number of bubble sources increases with increasing gas flow rate at lower gas flow rates (region I). At a further increase in gas flow rate, a coalescence of bubbles growing at neighboring sources occurred. Beyond this critical point, the number of bubble sources decreased with increasing gas flow rate (region II). Finally, a continuous linear blanket of gas was formed along the slot mouth.

3.2. Number of Bubble Sources

Figure 5 shows relationship between the number of bubble sources, \( n \), and gas flow rate, \( Q \). Although \( n \) of nozzles (a) and (b) are deviated at \( \text{We}=10^2 \), it may be considered that there is no effect of the slot width on the number of bubble sources in region II. According to the results, the number of bubble sources for the nozzle (b) is larger than that for the other. Large bubbles are formed at the nozzle.
and reduce the number of bubble sources. The transition from I to II region is found to occur at the same gas flow rate for nozzles (a), (b) and (d). On the other hand, when gas is injected through nozzle (c), the transition gas flow rate is larger than the other nozzles.

Figure 6 reveals the influence of wettability on the number of bubble sources. The number of bubble sources for the stainless steel slot nozzle is larger than that for the Teflon one. When the nozzle is wetted with water, fine bubbles generate from the slot. This increases the number of bubble sources at the gas exit of the slot nozzle.

Dimensional analysis of operative variables suggests a relationship between dimensionless average distance of bubble formation sites ($\lambda/w$) and the modified Weber number, $\text{We} = (U_s^2 w \rho) / \sigma$. Here, $\lambda$ is the distance between neighbouring bubble sources, $w$ is the slot width, $U_s$ (= $Q/wL$) is the superficial gas velocity, $\rho$ is the density of liquid, and $\sigma$ is the surface tension of liquid. Figure 7 shows relationship between $\lambda/w$ and the Weber number. When $\text{We} = 30 \sim 100$, the dimensionless distance between bubble sources becomes minimum. The solid line shows a following dimensionless correlation between $\lambda/w$ and the Weber number for the region II.

$$\lambda/w = 6.5 \text{We}^{0.466} \quad \text{............................(3)}$$

This correlation was obtained by the least square method with the experimental results for nozzles (a), (b) and (d). On the other hand, the measured value for nozzle (c) deviated from Eq.(2). In the case of nozzle (c), the width of the nozzle exit was expanded and much larger than the slot width. Then the bubble size became large and the number of bubble sources decreased. Hence the bubble formation behavior of nozzle (c) is different from those of other nozzles.

3.3. Mean Size of Bubbles

The relation between mean size of bubbles, $d_{B}$, and total gas flow rate, $Q$, is shown in Fig. 8. A number of models have been developed for predicting the bubble volume under the constant flow condition.\(^5\)\(^{-10}\) Most models show the bubble volume is calculated by the following equation.

$$V_B = k \left( \frac{Q}{g} \right)^{3/5} \quad \text{............................(4)}$$

where $k$ is the constant listed in Table 1 and $g$ is the gravitational acceleration.

In the present paper, a comparison was made between the prediction according to the Davidson and Schuler model\(^1\) and the experimental result. The constant, $k$, of the Davidson and Schuler model is 1.378 and nearly intermediate value among the other models.

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The bubble size increases with gas flow rate, \( Q \) for all slot nozzles. As seen from Fig. 8, the measured bubble diameter is smaller than that calculated from the Davidson and Schuler model. Since gas injected from the slot nozzle generates multi-formation sites of bubbles along the slot, the gas flow rate at each bubble source becomes smaller than the total gas flow rate, and hence, the bubble size is reduced. Therefore, when the total gas flow rate is the same, the bubble generated from the slot nozzle is much smaller than that from the orifice.

Figure 9 is a plot of the bubble size versus gas flow rate per bubble source, \( Q/n \), for nozzles (a) and (d). Although the bubble base expansion on a flat surface of nozzle (d) is observed, there is no substantial difference in bubble size between type (a) and type (d) nozzles. The bubble size calculated from the Davidson and Schuler model is also presented in the figure. The measurements corresponding to the gas injection through the stainless steel nozzle show a good agreement with the predictions. When gas is injected through the wetted slot nozzle, the bubble size is much smaller than that for the nonwetted slot nozzles when \( Q/n \) is smaller than \( 2 \times 10^{-5} \) m/s. Under the lower gas flow rates, the bubble volume is determined by the balance between the buoyancy force and the surface tension force.

\[
V_b = \frac{2\pi r_0 \sigma}{(\rho_l - \rho_g)g} \quad (5)
\]

where \( r_0 \) is the radius of bubble base. The bubble volume is independent of gas flow rate. Hence the measured values are larger than those predicted by the Davidson and Schuler model at the lower gas flow rates. The size of bubbles formed at the Teflon slot nozzles is smaller than that at the stainless steel nozzle when \( Q/n \) is larger than \( 2 \times 10^{-5} \) m/s. Under the higher gas flow rates, the liquid flow near the slot nozzle becomes much more intensive, hence the flow hastens the bubble detachment from the nozzle and the bubble size becomes smaller than the predicted value. This seems to be more remarkable for the bubble formation from the nonwetted nozzles and a further study is needed.

Figure 10 shows relationship between bubble size and gas flow rate per bubble source for nozzle (b). There is no effect of the slot width on the bubble size. The broken line is the result calculated according to the Davidson and Schuler model, while the solid line is a prediction by the equation derived by Sano et al.,11)
where $d_{no}$ is the outer diameter of nozzle. The experimental results obtained by using a single bubble source slot nozzle of 10 mm length are also shown in the figure. A good agreement between the prediction from Eq. (4) and the measurement for the narrow slot nozzle is obtained. Hence each bubble source can be considered as a single nozzle.

Figure 11 shows relationship between the bubble size for nozzle (c) and the gas flow rate per bubble source. The dotted line indicates the calculated value by the Davidson and Schuler model. The experimental results obtained by using a single bubble source slot nozzle of 10 mm length are also shown in the figure. The measured values are larger than the predicted ones. Since the bubble base for nozzle (c) spreads more widely than that for the other type nozzles, the bubble size becomes much larger.

4. Conclusions

The gas injection into the water bath through the slot nozzles of various types was studied. The results of the study can be summarized as follows.

(1) The dimensionless distance between neighbouring bubble sources of nozzles (a), (b) and (d) can be given by the following equation for the region II.

$$\lambda/w = 6.5 We^{0.466}$$

(2) The mean diameter of bubbles generated from the nozzles (a) and (d) is in good agreement with the diameter of bubbles calculated by the Davidson and Schuler model, when the gas flow rate is less than $1 \times 10^{-4}$ m$^3$/s. Hence, there was no substantial difference between the flat and uni-laterally inclined slot nozzles.

(3) As the measured bubble size of the nozzle (b) agrees with the calculated one by using Sano’s equation (Eq. (6)), each bubble source can be assumed as a single circular hole nozzle.

(4) For the wetted slot nozzle, the number of bubble sources was much larger and the bubble size was finer as compared with the nonwetted slot nozzle.

Acknowledgments

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