Steady and Periodical Bubble Attachment to the Sliding Gate in Immersion Nozzle

Daisuke MAEDA and Manabu IGUCHI

Graduate Student, Graduate School of Engineering, Hokkaido University, North 13, West 8, Kita-ku, Sapporo 060-8628 Japan.
1) Division of Materials Science and Engineering, Graduate School of Engineering, Hokkaido University, North 13, West 8, Kita-ku, Sapporo 060-8628 Japan.

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1. Introduction

The quality of steel products is closely associated with molten steel flow in the continuous casting mold. The flow is mainly governed by the structure of a sliding gate installed in the immersion nozzle. The flow rate of molten steel supplied into the mold is adjusted with the sliding gate by varying its opening. Ar gas is usually introduced into the immersion nozzle from the vicinity of the sliding gate to prevent attachment of nonmetallic inclusions to the inner wall of the immersion nozzle. A part of the Ar gas is disintegrated into bubbles of different diameters and they are carried into the molten steel flow, while the remaining part covers the inner wall of the immersion nozzle. According to a previous study,1,2,5) such unsteady bubble behavior may cause unsteady flows in the immersion nozzle and the mold, and hence, may cause mold powder entrapment near the meniscus of the mold.12,5)

It is widely known that bubbles preferably attach to a solid body of poor wettability.4,5) The wettability can be quantitatively evaluated in terms of contact angle, \( \theta \). The wettability of a solid is good when the contact angle, \( \theta \), is lower than 90°, while it is poor for 90° \( \leq \theta \leq 180° \). The attachment of Ar bubbles to the sliding gate is promoted as the contact angle of the sliding gate is increased. Information on bubble attachment to the sliding gate is limited.4,6) In this water model study, some of Ar bubbles attach to the sliding gate and detach nearly periodically from it under certain conditions. Such unsteady bubble behavior may cause unsteady flows in the immersion nozzle and the mold, and hence, may cause mold powder entrapment near the meniscus of the mold.1,2,5)

In this water model study, the effects of the opening of the sliding gate, molten steel flow rate, Ar gas flow rate, and wettability of the sliding gate on the Ar bubble attachment to the sliding gate were experimentally investigated.

2. Experiment

2.1. Experimental Apparatus and Procedure

Figure 1 shows a schematic of the experimental apparatus. The immersion nozzle and the sliding gate are made of transparent acrylic resin. Water and air were used as the model working fluids for molten steel and Ar gas, respectively. The inner diameter of the nozzle, \( D \), was 50 mm. The thickness and inner diameter of the sliding gate were 30 mm and 50 mm, respectively. The measurement method will be described in the following.

(1) Water was supplied into the immersion nozzle via a head tank and then circulated with a pump. Its flow rate was adjusted with a sluice valve.

(2) Air was supplied with a compressor through a glass pipe of an inner diameter of 0.4 mm. Its exit was located 230 mm above the sliding gate. The flow rate of air was adjusted with a mass flow controller.

(3) Bubble attachment to the sliding gate was observed for different gate openings with a high-speed video camera and a digital video camera, and by eye inspection. The gate opening was denoted by \( b \). It is zero for full opening and 50 mm for closing. The value of \( b \) was varied from 0 to 50 mm with equal intervals of 5 mm. The wettability of the sliding gate was changed by coating two kinds of repellents (Methaxylenehexafluoride and fluororesin) on it. Each repellent was also coated on the inner wall of the immersion nozzle. The area thus coated extended from 100 mm below the gate to 100 mm above the gate. These repellents were named the repellent A and repellent B, respectively. The contact angle of the original sliding gate made of acrylic resin was 67°. Those of the sliding gates coated with the repellents A and B were 107° and 144°, respectively. The life of the coating was approximately 1 h.

2.2. Determination of Experimental Condition

The cross-sectional mean velocity of molten steel flow, \( v_{\text{m}} \), in the real immersion nozzle for the slab continuous casting mold is the order of 1.0 m/s. We assume that the inner diameter of the nozzle, \( D \), is 0.10 m and the kinematic viscosity of molten steel, \( \nu_\text{m} \), is 1.0 \times 10^{-3} \text{ m}^2/\text{s}. The Reynolds number, \( \text{Re}_R \), is defined as

\[
\text{Re}_R = \frac{v_{\text{m}} D}{\nu_\text{m}}
\]

where the subscript, R, denotes the real process. Under this condition \( \text{Re}_R \) is given by

\[
\text{Re}_R = 1.0 \times 10^3
\]

In order to satisfy the Reynolds number similitude, the cross-sectional mean velocity in the model immersion nozzle should be given by

\[
v_{\text{m}} = \text{Re}_R \nu_\text{mR} = \frac{v_{\text{m}} \text{D}_{\text{LR}}}{\text{D}_{\text{LR}}} \nu_{\text{LR}}
\]

Substitution of \( v_{\text{m}} = 1.0 \times 10^{-4} \text{ m}^2/\text{s} \) and \( D = 0.050 \text{ m} \) into Eq. (3) yields

\[
v_{\text{m}} = 2.0 \text{ m/s}
\]

Accordingly, the water flow rate is given by

\[
Q_{\text{w}} = \pi D^2 v_{\text{m}} / 4 = 4 \times 10^{-3} \text{ m}^3/\text{s} = 4 \text{ L/s} = 240 \text{ L/min}
\]

This water flow rate cannot be realized in the presently used model immersion nozzle. Fortunately, as the flow in the real immersion nozzle is turbulent, relaxation of the Reynolds number similitude is allowed. The water flow rate therefore was set to be 26 to 60 L/min. Although the Reynolds number in the model reduced to the order of magnitude of 1 \times 10^4, the flow in the model immersion nozzle is still turbulent.

When Ar gas is introduced into the immersion nozzle, an Ar gas–molten steel two-phase flow is generated in the immersion nozzle. The behavior of this flow is governed by the superficial velocities of Ar gas and molten steel, \( v_{\text{sp}, \text{gr}} \) and \( v_{\text{sp}, \text{LR}} \).

\[
v_{\text{sp}, \text{gr}} = 4Q_{\text{gr}} / \pi D_{\text{LR}}^2
\]

\[
v_{\text{sp}, \text{LR}} = 4Q_{\text{LR}} / \pi D_{\text{LR}}^2
\]

This fact suggests that a ratio of air flow rate to water flow rate in the model immersion nozzle, \( Q_{\text{gr}} / Q_{\text{LR}} \), must be equal to the value in the real immersion nozzle. The gas flow rate therefore was chosen to be 5, 10, and 20 cm/s, so that the ratio of air flow rate to liquid flow rate falls in the range of the real flow rate ratio, \( Q_{\text{gr}} / Q_{\text{LR}} \). The mean diameter of bubbles is approximately 6 mm under the present experimental conditions.
3. Experimental Results and Discussion

3.1. Classification of Bubble Attachment Patterns

3.1.1. Wetted Sliding Gate

Figure 2 shows patterns of steady bubble attachment to the wetted sliding gate of \( \theta_s = 67^\circ \). Bubbles attach preferably to the flow separation regions on and around the sliding gate. The steady bubble attachment patterns can be basically classified into 4 categories, (A)–(D). The same patterns were observed for \( \theta_s = 67^\circ \) and \( \theta_s = 107^\circ \).

In addition, an unsteady bubble attachment pattern was observed for a relatively small sliding gate opening, \( b \), as shown in Fig. 3. Strictly speaking, this pattern was observed for \( b = 10 \) mm and \( \theta_s = 67^\circ \) and for \( b = 10 \) mm and \( \theta_s = 107^\circ \). A bubble attaches to the right wall of the immersion nozzle just below the sliding gate and grows with time. When the volume of the bubble reaches a certain critical value, it shifts to the left wall of the sliding gate due to an excess buoyancy force acting on it. Subsequently, another bubble attaches to the right wall of the immersion nozzle below the sliding gate. This bubble also shifts to the left wall of the sliding gate just like the previous one. Such a periodical phenomenon is repeated until the bubble growing on the left hand side of the sliding gate detaches from it due to an excess buoyancy force. As a result, the state returns to its initial one.

3.1.2. Poorly Wetted Sliding Gate

Figure 4 shows four patterns of steady bubble attachment to the poorly wetted sliding gate of \( \theta_s = 144^\circ \). The pattern (E) indicates that a donut-like bubble attaches to the whole sliding gate surface, and water descends near the central part of the sliding gate. In the pattern (F), a donut-like bubble still attaches to the upper part of the sliding gate. A bubble attaches to the left hand side of the immersion nozzle located just below the sliding gate. With a further increase in \( b \), two attaching bubbles were observed. One bubble attaches to the sliding gate and the other bubble attaches to the left hand side of the immersion nozzle. This pattern was named pattern (G). When \( b \) is very large, a single bubble attaches to the left hand side of the immersion nozzle (pattern (H)).

An unsteady bubble attachment pattern named pattern (J) was also observed for \( \theta_s = 144^\circ \), as shown in Fig. 5. The pattern (J) appears for \( b = 5 \) and 10 mm. A donut-like bubble growing on the sliding gate detaches periodically from it and rises upward.

3.2. Bubble Attachment Pattern Map

Figures 6 through 8 show the bubble attachment pattern maps as functions of the water flow rate, \( Q_L \), and sliding gate opening, \( b \). When the sliding gate is wetted by water (\( \theta_s = 67^\circ \), Fig. 6), the steady bubble attachment pattern shifts basically in the following manner with an increase in \( b \):

\[(A) \rightarrow (B) \rightarrow (C) \rightarrow (D) \rightarrow (A)\]

The same tendency can be seen when \( Q_L \) is increased. When the separation region is very small, no bubble attachment takes place, as can be seen in the pattern (A). The same tendency as above was observed in a poorly wetted case of \( \theta_s = 107^\circ \) (see Fig. 7). The unsteady pattern (I) ap-
pears for a relatively small sliding gate opening. The steady bubble attachment pattern for \( \theta_c = 144^\circ \) shifted basically in the following manner as the sliding gate opening, \( b \), was increased.

\[
(E) \rightarrow (F) \rightarrow (G) \rightarrow (H) \rightarrow (A)
\]

The gas flow rate, \( Q_g \), hardly affected the bubble attachment pattern map under the present experimental conditions (\( Q_g = 5\text{–}20 \text{ cm}^3/\text{s} \)).

3.3. Period of Unsteady Bubble Attachment to Sliding Gate

The period, \( T_S \), for the periodical attachment of a bubble is shown against the water flow rate, \( Q_w \), in Fig. 9. The measured value of \( T_S \) for \( \theta_c = 67^\circ \text{ and } 107^\circ \) increased with an increase in \( Q_w \). This is because the hydrodynamic drag acting on a bubble increases with \( Q_w \) and, as a result, the bubble can stay in the flow separation region on the sliding gate for a longer time. On the other hand, the period for \( \theta_c = 144^\circ \) decreased with an increase in \( Q_w \). A donut-like bubble attaches to the surface of the sliding gate in this case, and hence, an elevated hydrodynamic force suppresses the bubble to attach to the sliding gate. Further investigation is desirable for a better understanding of the period, \( T_S \).

3.4. Applicability of the Presently Obtained Findings to Real Immersion Nozzle

A bubble attaching to the sliding gate is subjected to the hydrodynamic force, buoyancy force, and surface tension force, \( F_{\text{hyd}}, F_{\text{buoy}}, \) and \( F_s \) being expressed by

\[
F_{\text{hyd}} = C_D A_B \rho_B V_B^2 / 2 \quad \text{ .................................. (7)}
\]

\[
F_{\text{buoy}} = (\rho_B - \rho) g V_B \approx \rho_B g V_B \quad \text{ .................................. (8)}
\]

\[
F_s = \sigma (\cos \theta_a - \cos \theta_r) L_B \quad \text{ .................................. (9)}
\]

where \( C_D \) is the drag coefficient, \( A_B \) is the projected area of the bubble, \( g \) is the acceleration due to gravity, \( V_B \) is the volume of the bubble, \( \sigma \) is the surface tension, \( \theta_a \) is the receding contact angle, \( \theta_r \) is the advancing contact angle, and \( L_B \) is the horizontal length of the bubble in contact with the sliding gate. The former two forces act in the opposite directions. When the bubble is stationary on the sliding gate, the direction of the surface tension force is the same as that of the smaller one of the former two forces.

We assume that the sliding gate in the model has the same dimensions as those of the real sliding gate. We further assume that the shape and size of a bubble attaching to the sliding gate are the same between the model and real process. When the liquid flow rate and the receding and advancing contact angles in the model are the same as those in the real process, the ratio of the hydrodynamic drag to the buoyancy force in the model is equal to that in the real process, because these forces are governed by the density of liquid as seen in Eqs. (7) and (8). For example, the buoyancy force in the real process is approximately seven times as large as that in the model. The same is true for the hydrodynamic drag. These facts mean that the Froude number similitude is satisfied. The surface tension in the real process, however, is approximately 20 times as large as that in the model, and, as a result, a larger bubble can stay on the real sliding gate than on the model sliding gate. The Weber number similitude therefore is not satisfied. Further investigations are also required for drawing a comprehensive bubble attachment map by changing the surface tension and contact angle over a wide range.

Unsteady molten steel flows in the real immersion nozzle and mold seem to be caused by the presently observed unsteady bubble attachment to the sliding gate. Detailed information on the unsteady flow however is required to confirm this prediction.

4. Conclusions

(1) Patterns of bubble attachment to the sliding gate were correlated as functions of the sliding gate opening, \( b \), water flow rate, \( Q_w \), gas flow rate, \( Q_g \), and the wettability of the sliding gate. The patterns were classified into steady and periodical attachment types.

(2) As the wettability of the sliding gate becomes poor, the bubble attachment is promoted. The area of the bubble attachment region is also increased.

(3) Periodical bubble attachment to the sliding gate was observed under certain conditions. The period of the periodical bubble attachment increased with an increase in \( Q_w \), for \( \theta_c = 67^\circ \text{ and } 107^\circ \), while it decreased with \( Q_w \) for \( \theta_c = 144^\circ \).

REFERENCES

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Fig. 7. Observed regimes of bubble patterns attaching to sliding gate (\( \theta_c = 107^\circ \) and \( Q_w = 10 \text{ cm}^3/\text{s} \)).

Fig. 8. Observed regimes of bubble patterns attaching to sliding gate (\( \theta_c = 144^\circ \) and \( Q_w = 10 \text{ cm}^3/\text{s} \)).

Fig. 9. Period of periodical attachment of bubbles.