Water Model Experiments on the Effect of an Argon Bubble on the Meniscus Near the Immersion Nozzle

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Water model experiments have been carried out to understand the behavior of the meniscus of molten steel near the immersion nozzle. The meniscus is disturbed by a large argon bubble rising along the immersion nozzle. Water, silicone oil, and air are used as models for molten steel, mold powder, and argon, respectively. A cylindrical rod is used as a model for the immersion nozzle. The contact angle of a water droplet on the rod is adjusted to become nearly the same as that of a molten steel droplet on the immersion nozzle by coating repellent on the rod surface. A single air bubble of a predetermined volume is released from a cap-shaped container to attach to the bottom of the rod. The behavior of the bubble passing across the interface between water and silicone oil is observed with a high-speed video camera to make clear the entrapment of silicone oil droplets into the water bath.

KEY WORDS: continuous casting; immersion nozzle; argon bubble; mold powder entrapment; interfacial tension; wettability.

1. Introduction

Many investigations have been carried out to understand the mechanism of mold powder entrapment into the molten steel in the continuous casting mold1–5) and the dynamic behaviors of inclusions in the mold.6,7) The entrapment mechanisms proposed so far can be summarized as follows,4 as schematically shown in Fig. 1.

(1) Entrapment caused by steady reversing flow from the narrow face
(2) Entrapment associated with Karman’s vortex streets behind the immersion nozzle
(3) Entrapment forced by attack of a large argon bubble rising near the immersion nozzle onto the meniscus. Such a bubble is generated at the nozzle port because argon gas is introduced into the immersion nozzle from a porous plate placed near the sliding gate to prevent attachment of alumina onto the inner wall of the immersion nozzle.8–10)
(4) Entrapment due to the Kelvin–Helmholz instability appearing at an interface between molten steel and mold powder layers
(5) Entrapment induced by vertical pressure difference along the outer surface of the immersion nozzle.

The critical molten steel velocities describing the mold powder entrapment were calculated based on the above-mentioned mechanisms except for the mechanism (3). The values thus calculated were nearly the same with one another and, accordingly, it is difficult at present to predict the most influential mechanism for the entrapment. Accordingly, further precise discussion should be given on each mechanism. In this study attention was paid on the mechanism (3).

In a previous study,11) the authors observed that air bubbles preferably attach to a vertically placed cylindrical rod of poor wettability. The contact angle, \( \theta_c \), is usually used for quantitatively describing the wettability.12 Consider the case that a liquid droplet is placed on a solid plate. The solid plate is wetted by that liquid for \( 0^\circ \leq \theta_c < 90^\circ \), while poorly wetted for \( 90^\circ \leq \theta_c \leq 180^\circ \).

The velocity of a bubble rising along a poorly wetted rod was much higher than that of a bubble rising away from the rod. Concerning the clarification of the mechanism (3), attention was paid in a previous paper13) only to a bubble rising away from the immersion nozzle. If an argon bubble rises along the real immersion nozzle, the molten steel moving upward with the bubble also has a high rising ve-
locity. This means that the bubble exerts a stronger effect on the meniscus than a bubble rising away from the nozzle.

The objective of this study is to make clear the behavior of mold powder disturbed by a large argon bubble rising along the immersion nozzle based on water model experiments.

2. Experimental Apparatus

Figure 2 shows a schematic of the experimental apparatus. Water was partially filled in an acrylic resin vessel to a prescribed depth of 30 cm. Silicone oil of a kinematic viscosity of 10 mm²/s and a density of 935 kg/m³ was placed on the surface of the water bath. The thickness of the silicone oil layer was chosen to be 4.0 cm by referring to previous papers.13,14) A single bubble of a volume of 1, 5, 10, 15, or 25 cm³ was generated with a hemispherical cap. Air of a predetermined volume was supplied into the cup with a syringe. The cup was turned over to release a single bubble. A cylindrical rod made of transparent acrylic resin was placed slightly above the cup and hence the bubble collided to the bottom of the rod. The distance from the bottom of the vessel to the bottom of the rod was 5 cm. The diameter of the rod was 1.0, 1.6 and 2.5 cm. The contact angle of a water droplet placed on the rod surface was 77° and, accordingly, the rod was originally wetted by water. When the wettability of the rod was good, the bubble rose near the rod without directly attaching to it. The surface of the rod was coated with repellent to change its wettability to be poor. The contact angle resulted in 144°. The rod was placed on the centerline of the bath just like the wetted one.

The behavior of a single bubble rising near the immersion nozzle was observed with a high-speed video camera at 100 fps and the images were recorded on a personal computer. The rising velocity of the bubble was obtained by dividing its vertical displacement by the predetermined time increment.15)

3. Experimental Results and Discussion

3.1. Behavior of Bath Surface in the Absence of Silicone Oil Layer

3.1.1. Bubble Behavior in the Absence of Cylindrical Rod

As a first step, the behavior of the bath surface disturbed by a single bubble was observed with a high-speed video camera. The cylindrical rod was absent. This situation corresponds to the case that a single bubble ascends far away from the immersion nozzle. The bath depth was 30 cm. The bubble ruptured in the course of leaving the bath surface. According to previous investigations, two types of rupture phenomena exist with respect to the volume of the bubble,16) as shown in Fig. 3. When the volume is smaller than a certain critical value, a micro jet is generated and the liquid in the wake of the bubble is pulled up into the air. This droplet is called the jet drop. On the other hand, when the volume is greater than the critical value, a liquid film covering the upper part of the bubble breaks up and, as a result, many small droplets are formed above the bath surface. These droplets are named the film droplets. At present, the critical bubble volume is not known yet even for the water and air system.

In this study only film droplets were observed when a single bubble of a volume ranging from 1 to 25 cm³ passed across the bath surface, as shown in Fig. 4. At the same time, bubbles of diameters over a wide range were entrapped into the bath. The penetration of bubble was not so great. Namely, the entrapped bubbles remained just below the bath surface.

3.1.2. Bubble Behavior in the Presence of Cylindrical Rod

The bath depth was 30 cm just as in the former case. Figure 5 shows photographs of a rising single bubble in the presence of a poorly wetted cylindrical rod. The diameter of the rod was 1.0 cm. The volumes of bubble were 1, 10, and 25 cm³. In each case, a single bubble attached preferably to a cylindrical rod of a contact angle, θ cornerstone, of 144°, as explained in detail in the previous paper.15) It rose along the rod even after it passed through the bath surface. The liquid film covering the upper part of the bubble ruptured at a certain distance from the bath surface and, as a result, some droplets were generated just like the film droplets shown in Fig. 3. The droplets arrived at high positions in the air.

Meanwhile, entrainment of small bubbles into the bath was not observed when a bubble of a volume of V = 1 cm³ passed across the bath surface. Even when the bubble volume was increased up to 25 cm³, the number of entrapped bubbles was limited. The same tendency was observed for D = 2.5 cm, as shown in Fig. 6.

3.2. Behavior of a Single Bubble Passing across the Interface between Water and Silicone Oil Layers

3.2.1. Behavior of a Single Bubble in the Absence of a Cylindrical Rod

The bath depth was 30 cm and the thickness of the sili-
cone oil layer was 4 cm, as mentioned earlier. The behavior of a single bubble passing through the stratified water and silicone oil layers depended strongly on the volume of the bubble, as shown in Fig. 7. Concerning a bubble of $V_B = 1 \text{ cm}^3$, the water moving after the bubble penetrated into the upper silicone oil layer without breaking up. Namely, a water column was formed behind the bubble.\(^{17,18}\) After a while, it broke out into some water droplets. The number of water droplets thus generated increased with an increase in the bubble volume, $V_B$. At the same time, a part of the bubble disintegrated into many small bubbles around the interface between the water and silicone oil layers. This is because the flow field around the interface is highly disturbed due to arrival of the bubble itself. The water droplets and bubbles thus newly generated around the interface were highly mixed there.
3.2.2. Behavior of a Single Bubble in the Presence of a Poorly Wetted Cylindrical Rod

(1) Interface between Water and Silicone Oil Just after the Immersion of Rod

As mentioned earlier, the cylindrical rod used in this study was poorly wetted by water and highly wetted by silicone oil. Figure 8 shows a snapshot of the interface between the silicone oil and water layers in the presence of the cylindrical rod of $D=2.5\,\text{cm}$. The upper photograph, Fig. 8(a), was taken just after the cylinder was immersed in the bath. The interface descended along the rod to a certain distance from the initial interface position. The distance from the initial interface position to the position thus descended along the rod will be estimated below.

For the sake of simplicity, the rod surface is assumed to be flat. Figure 9 shows a flat plate immersed in a liquid. The elevated position of the liquid on the plate surface is expressed by

$$h=\frac{(2/c_{12})}{g}\sin\left[(90^\circ-\theta_c)/2\right] \quad \text{.....(1)}$$

where $g$ is the acceleration due to gravity, $\theta_c$ is the contact angle, $\rho_1$ and $\rho_2$ are the densities of the upper and the lower fluids, respectively, and $\sigma_{12}$ is the interfacial tension. In this experiment $\rho_1=935\,\text{kg/m}^3$, $\rho_2=997\,\text{kg/m}^3$ and $\sigma_{12}=52.7\,\text{mN/m}$.

The contact angle, $\theta_c$, in Eq. (1) can be calculated in the following manner. The contact angle of the silicone oil on the presently used cylindrical rod is approximately $0^\circ$. As a result, the contact angle of a water droplet placed on the repellent coated wall and surrounded by the silicone oil can be calculated from the following relationship.

$$\cos \theta_c = (\sigma_2 \cos \theta_{c_2} - \sigma_1 \cos \theta_{c_1})/\sigma_{12} \quad \text{.....(3)}$$

where $\theta_{c_1}$ is the contact angle of silicone oil and $\theta_{c_2}$ is the contact angle of water. Equation (3) gives

$$\theta_c = 180^\circ \quad \text{.....(4)}$$

Substituting $\theta_c=180^\circ$, $\rho_1=935\,\text{kg/m}^3$, $\rho_2=997\,\text{kg/m}^3$ and $\sigma_{12}=52.7\,\text{mN/m}$ into Eq. (1) yields

$$c=(\rho_2-\rho_1)g/\sigma_{12} \quad \text{.....(2)}$$
This minus sign means that the interface of the silicone oil and water descends along the rod. The observed value of \( h \) was approximately \( 1.2 \text{ m} \), as shown in Fig. 8(a). Agreement between the estimated and observed values was satisfactorily good.

As \( \delta_s \) is much smaller than \( D \), the capillary force balance in a steady state is described by

\[
\pi D \sigma_1 \cos \theta_1 = \pi D \delta_s \rho_o (\rho_2 - \rho_1) g \tag{6}
\]

where \( \theta_1 \) is the contact angle of silicone oil. The final depth of the silicone oil, \( h_{\text{final}} \), is expressed by

\[
h_{\text{final}} = \sigma_1 \cos \theta_1 \left[ \delta_s (\rho_2 - \rho_1) g \right] \tag{7}
\]

Substituting \( \sigma_1 = 20.1 \text{ mN/m}, \ \theta_1 = 0^\circ, \ \delta_s = 15 \text{ \mu m}, \ \rho_2 = 997 \text{ kg/m}^3, \ \rho_1 = 935 \text{ kg/m}^3 \) into Eq. (7) gives

\[
h_{\text{final}} = 2.21 \text{ m} \tag{8}
\]

(2) Descending Behavior of the Interface along the Rod

With a further lapse of time the interface being in contact with the rod surface descended gradually to a deeper position, as shown in Fig. 10. Discussion will be given on this phenomenon. The capillary motion of the silicone oil is considered to play an essential role on this phenomenon. The surface of the rod covered with the repellent was rough because fine particles were contained in the repellent. A very small air bubble can be captured in each valley of the coating layer because the rod was initially placed in the atmosphere and covered with air. It is difficult to remove such bubbles under the present experimental conditions. We assume that the silicone oil descends through this very thin air layer. The thickness of the air layer, \( \delta_a \), was evaluated to be \( 15 \text{ \mu m} \) based on the surface roughness measurement. This is because the maximum roughness height was approximately \( 15 \text{ \mu m} \).

This thickness is much smaller than \( D \), the capillary force balance in a steady state is described by

\[
p D \sigma_1 \cos \theta_1 = p D \delta_s \rho_o (\rho_2 - \rho_1) g - p D h_s \rho_1 g + p (D + 2 \delta_s) h_s \tau_c \tag{9}
\]

where \( h_s \) is the penetration depth of silicone oil layer on the rod surface and \( \tau_c \) denotes the laminar shear stress acting on the wall and the vertical interface between water and silicone oil. The first and the second terms on the left-hand side of Eq. (9) denote the capillary force and gravitational force acting on the silicone oil, respectively. Meanwhile, the first, second, and third terms on the right-hand side of Eq. (9) denote the buoyancy force acting on the silicone oil, the shear stress on the surface of the rod, and shear stress on the interface between the silicone oil and water, respectively. The shear stress was evaluated by assuming that the flow field under consideration is the same as that in two parallel plates. In addition, \( \mu_o \) is the dynamic viscosity of silicone oil.

Substituting Eq. (10) into Eq. (9) gives the following differential equation under the assumption of \( \delta_s << D \).

\[
dh_s/dt + A - B/h_s = 0 \tag{11}
\]
\[ A = \delta s^n \left( \rho_s - \rho_1 \right) / \left( 6 \mu_s \right) \] \( \cdots \cdots \cdot (12) \]

\[ B = \delta c \sigma s \cos \theta c s / \left( 6 \mu s \right) \] \( \cdots \cdots \cdot (13) \]

Equation (11) can be solved with the following initial condition.

\[ h_s = h_{\text{io}} \quad \text{at} \quad t = 0 \] \( \cdots \cdots \cdot (14) \]

The solution of Eq. (11) is given by

\[ t = \left( B / A^2 \right) \ln \left( \left( B - Ah_s \right) / \left( B - Ah_{\text{io}} \right) \right) - \left( h_s - h_{\text{io}} \right) / A \] \( \cdots \cdots \cdot (15) \]

The measured values of \( h_s \) are plotted with open circles in Fig. 11. Its initial value, \( h_{\text{io}} \), was 1.5 cm. The value of \( h_s \) calculated from Eq. (15) for \( \delta s = 15 \mu m \) is drawn by a solid line in Fig. 11. Agreement between the measured values and the calculated result is satisfactorily good, suggesting that the silicone oil descends following the presently proposed mechanism. Namely, the silicone oil descends through a thin air layer existing on the surface of the poorly wetted cylindrical rod.

(4) Behavior of a Single Bubble Rising along a Cylindrical Rod

A single bubble rose along a cylindrical rod until it arrived at the water and silicone oil interface on the surface of the rod, as shown in Fig. 12. In these cases \( h_s \) was 10 cm. The bubble departed from the rod surface and then behaved just like a bubble rising in the absence of a cylindrical rod. Consequently, the behaviors of an initial single bubble and the resultant water droplets, silicone oil droplets and small bubbles near the interface were nearly the same as those in the absence of the rod.

3.3. Rising Velocity of a Single Bubble in the Water and Silicone Oil Layers

3.3.1. Rising Velocity of a Single Bubble in the Absence of a Poorly Wetted Cylindrical Rod

Figure 13 shows the measured values of rising velocity of a bubble near the interface between the water and silicone oil layers in the absence of a cylindrical rod. The rising velocity decreased slightly at the interface but returned to around its initial value just above the interface in every case.

3.3.2. Rising Velocity of a Single Bubble in the Presence of a Poorly Wetted Cylindrical Rod

Although the initial interface between the water and silicone oil layers was located at \( z = 30 \) cm, bubble rising velocity measurements were carried out after the silicone oil penetrated to the bottom of the rod. Namely, the penetration depth, \( h_s \), was 25 cm. As each bubble detached from the rod, the measured bubble rising velocity was almost independent of the rod diameter and agreed with the value observed in the absence of a cylindrical rod, as can be seen in Fig. 14.
3.3.3. Rising Velocity of a Single Bubble in the Real Continuous Casting Mold

If the mold powder in the real continuous casting mold penetrates into the molten steel along the outer surface of the immersion nozzle, the rising velocity of an argon bubble would not be affected by the immersion nozzle. The mold powder entrapment by the argon bubble also would not be dependent on the presence of the immersion nozzle. Further investigation is desirable to confirm this presumption.

3.4. Proposal of a New Mechanism for Mold Powder Entrapment

The presently observed downward penetration of silicone oil along the surface of a poorly wetted rod suggests that the mold powder penetrates along the real immersion nozzle under a certain condition, arrives at the two ports of the nozzle and then it is entrapped into the mold by the molten steel flow issuing out of the two ports. No one has mentioned about this entrapment mechanism. Accordingly, this mechanism is regarded as the sixth entrapment mechanism. Further experiment also is required for the clarification of a possibility of mold powder entrapment caused by this mechanism.

4. Conclusions

(1) A single bubble rising in a bath without an immersion cylindrical rod ruptured at the bath surface. The so-called film droplets appeared under the experimental conditions considered in this study.

(2) A single bubble rising along a cylindrical rod of a contact angle, \(\theta_{c2}\), of 144° penetrated into the air along the rod. The liquid film covering the bubble ruptured in the course of rising along the rod and finally it broke up into some droplets.

(3) In the case that silicone oil was placed on the surface of the water bath, a single bubble initially released in the water layer penetrated into the silicone oil layer. When a cylindrical rod of poor wettability was absent and the bubble volume, \(V_{ib}\), was 1 cm\(^3\), the interface between the two layers was hardly disturbed by the bubble. The water engulfed into the wake of the bubble was pulled up into the upper silicone oil layer. A water column was generated behind the bubble and it broke up into a few water droplets. On the other hand, when the bubble volume, \(V_{ib}\), was greater than 10 cm\(^3\), the interface was significantly disturbed by the bubble. Many water droplets, silicone oil droplets and small bubbles were simultaneously generated around the interface between the water and silicone oil layers. The two layers were highly mixed by the single bubble.

(4) Silicone oil penetrated downwards along the rod due to the capillary force. The relationship between the penetration depth and time was satisfactorily predicted by an analytical solution derived in this study.

(5) A bubble did not attach to the rod covered with the silicone oil. The rising velocity of the bubble almost agreed with that of a bubble rising away from the rod.

(6) A new mechanism for the mold powder entrapment was proposed.

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Nomenclature

- \(A, B\): Quantities defined by Eqs. (12) and (13)
- \(c\): Capillary parameter
- \(D\): Diameter of cylindrical rod
- \(g\): Acceleration due to gravity
- \(H\): Bath depth
- \(h\): Height of interface between water and silicone oil on the rod surface
- \(h_0\): Penetration depth of interface between water and silicone oil on the rod surface
- \(h_{01}\): Initial value of \(h_0\)
- \(h_{11}\): Final value of \(h_0\)
- \(t\): Time
- \(z\): Axial distance
- \(\delta\): Thickness of capillary passage
- \(\mu_c\): Dynamic viscosity of silicone oil
- \(\theta_{c1}\): Contact angle
- \(\theta_{c2}\): Contact angle of silicone oil
- \(\theta_{w}\): Contact angle of water
- \(\rho_1, \rho_2\): Densities of silicone oil and water, respectively
- \(\sigma_{11}, \sigma_{22}\): Surface tensions of silicone oil and water, respectively
- \(\sigma_{12}\): Interfacial tension

REFERENCES

1) S. Asai: 100th and 101st Nishiyama Memorial Seminar, ISIJ, Tokyo, (1984), 1114.
2) JSPS 19th Committee: Recent Development in Studies of Nonmetallic Inclusions in Steel, JSPS, (1994).
3) M. Iguchi, J. Yoshida, T. Shimizu and Y. Mizuno: ISIJ Int., 40 (2000), No. 7, 685.
4) J. Yoshida, M. Iguchi and S. Yokoya: Tetsu-to-Hagané, 87 (2001), No. 8, 529.
5) J. Yoshida, M. Iguchi and S. Yokoya: Tetsu-to-Hagané, 87 (2001), No. 12, 741.
6) H. Lei and J.-C. He: Steel Res. Int., 78 (2007), No. 9, 704.
7) L. B. Trindade, J. E. A. Nadalon, A. C. F. Vilela, M. T. M. B. Vilhena and R. B. Soares: Steel Res. Int., 78 (2007), No. 9, 708.
8) K. Sasaki and Y. Mizukami: CAMP-ISIJ, 8 (1995), 338.
9) H. Suzuki, Y. Yoshimura, M. Ogata and N. Imai: Shinagawa Tech. Rep., 46 (2003), 67.
10) Z. Wang, K. Mukai and D. Izu: ISIJ Int., 39 (1999), No. 2, 154.
11) K. Fukushi and M. Iguchi: J. JSEM, 4 (2004), No. 3, 192.
12) K. Ichikawa and I. Lin: CAMP-ISIJ, 13 (2000), 170.
13) S. Yamashita and M. Iguchi: ISIJ Int., 41 (2001), No. 12, 1529.
14) S. Yamashita and M. Iguchi: ISIJ Int., 43 (2003), No. 9, 1326.
15) T. Watanabe and M. Iguchi: Tetsu-to-Hagané, 94 (2008), No. 8.
16) T. Uchida and M. Iguchi: J. Materials Processing and Manufacturing Science, 8 (2000), No. 1, 256.
17) G. Reiter and K. Schwertfeger: ISIJ Int., 32 (1992), 50.
18) G. Reiter and K. Schwertfeger: ISIJ Int., 32 (1992), 57.
19) K. L. Mittal: Contact Angle, Wettability and Adhesion, VSP, Utrecht, (1993), 237.