Note

Prediction of Argon Gas Attachment to Sliding Gate in Immersion Nozzle

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1. Introduction

Argon gas is often introduced into the immersion nozzle of the continuous casting process to prevent adhesion of nonmetallic inclusions such as alumina on the inner wall of the immersion nozzle.¹⁾ Previous water model experiments^{2,3)} suggest that the argon gas thus introduced attaches preferably to the sliding gate under a specific condition. The velocity of molten steel flow passing through the sliding gate is strongly affected by the attached gas.³⁾ As a result, a biased flow is induced in the continuous casting mold. When the biased flow is pronounced, the velocity of meniscus flow sometimes exceeds a certain critical value and then mold powder is entrapped into the molten steel in the mold^{1,4,5)} to cause defects of steel products. In this study a prediction method is proposed for the critical molten steel flow rate causing argon gas attachment to the sliding gate.

2. Prediction of Critical Condition for Argon Gas Attachment to Sliding Gate

The present authors investigated previously on bubble removal from an air–water two-phase flow descending in a circular pipe using an inversely oriented Y-junction.⁶⁾ The main pipe of the Y-junction was connected to the lower end of the circular pipe. The acrylic Y-junction was originally wetted by water. One side of the Y-junction was coated with fluororesin to change its wettability. The fluororesin coated wall became poorly wetted by water. A critical condition for air to be stably in contact with the poorly wetted wall as an air film was determined on the basis of a force balance for a bubble attaching to the wall. The critical condition is expressed by the following semi-empirical equations depending on the gas flow rate in the main pipe of the Y-junction.

$$j_g + j_L < 7.1 [g\sigma(\cos \theta_r - \cos \theta_a)/\rho_L]^{1/4} \quad \text{(lower gas flow rate regime)} \quad (1)$$

$$j_L < 4.5 [g\sigma(\cos \theta_r - \cos \theta_a)/\rho_L]^{1/4} \quad \text{(higher gas flow rate regime)} \quad (2)$$

$$j_g = Q_g/A \quad (3)$$

$$j_L = Q_L/A \quad (4)$$

$$A = \pi D^2/4 \quad (5)$$

where j_g is the superficial velocity of gas, j_L is the superficial velocity of liquid, g is the acceleration due to gravity, σ is the surface tension of liquid, θ_r is the receding contact angle, θ_a is the advancing contact angle, ρ_L is the density of liquid, Q_g and Q_L are the gas and liquid flow rates, respectively, and A and D are the cross-sectional area and diameter of the main pipe, respectively.

Equation (1) is valid for a lower gas flow rate regime, while Eq. (2) is valid for a higher gas flow rate regime. The boundary of the applicable gas flow rate regimes of Eqs. (1) and (2) can be determined by equating them. When Eq. (1) or (2) is satisfied, an air film can exist on the wall. Otherwise, a bubble once attached to the wall is carried away from the wall by water flow.

We assume that Eqs. (1) and (2) are valid for air film attachment to the sliding gate, too. The cross-sectional area, A , however should be replaced by the opening area of the sliding gate, A_s . Figure 1 shows a schematic of the cross-section of the sliding gate, where R is the radius of the immersion nozzle, b is the displacement of the sliding gate. The thickness of the sliding gate is 30 mm. The opening area of the sliding gate, A_s , can be given by

$$A_s = 2R^2\theta - 2aR \sin \theta \quad (6)$$

$$a = b/2 \quad (7)$$

$$R = D/2 \quad (8)$$

$$\theta = \cos^{-1}(b/D) \quad (9)$$

where D is the diameter of the immersion nozzle.

In the previous water model experiments³⁾ a lot of air was supplied into the immersion nozzle. Equation (2) was therefore chosen here for the comparison with experimentally determined boundary between the regimes with and without air film attachment to the sliding gate. Equation (2) is rewritten as

$$Q_L/A_s < 4.5 [g\sigma(\cos \theta_r - \cos \theta_a)/\rho_L]^{1/4} \quad (10)$$

If the above-mentioned assumption holds, air film attachment occurs in the liquid flow rate regime where Eq. (10) is satisfied. The boundary of this regime is given by

Fig. 1. Cross-section of sliding gate.

$$Q_L = 4.5A_s[g\sigma(\cos\theta_r - \cos\theta_a)/\rho_L]^{1/4} \dots\dots\dots(11)$$

According to previous water model experiments⁷⁾ and the present experiment, the advancing and receding contact angles, θ_a and θ_r , are known for three kinds of sliding gates and the boundary for each gate is calculated from Eq. (11) as follows:

(1) Acrylic sliding gate

$$\theta_a = 85^\circ, \quad \theta_r = 28^\circ \dots\dots\dots(12)$$

$$Q_L = 69.7A_s \text{ cm}^3/\text{s} \dots\dots\dots(13)$$

(2) Liquid paraffin (repellent 1) coated sliding gate

$$\theta_a = 104^\circ, \quad \theta_r = 50^\circ \dots\dots\dots(14)$$

$$Q_L = 71.6A_s \text{ cm}^3/\text{s} \dots\dots\dots(15)$$

(3) Fluororesin (repellent 2) coated sliding gate

$$\theta_a = 120^\circ, \quad \theta_r = 79^\circ \dots\dots\dots(16)$$

$$Q_L = 67.2A_s \text{ cm}^3/\text{s} \dots\dots\dots(17)$$

3. Comparison of Predicted with Experimentally Determined Boundaries of Regimes with and without Air Film Attachment

Figures 2 through 4 compare the predicted boundary with experimentally determined one for the acrylic gate, liquid paraffin coated gate, and fluororesin coated gate, respectively. The diameter, D , is 50 mm.³⁾ The predicted boundary indicated by a broken line in every figure should be compared with the lower edge of the regime denoted by Type A in which air film attachment never occurs. The predicted boundary is favorably in agreement with the experimentally determined one in Figs. 2 and 3. Equation (11) slightly underestimates the boundary in Fig. 4. The coefficient of Eq. (11) therefore is modified to best fit the experimentally determined boundary in Fig. 4.

$$Q_L = 5.9A_s[g\sigma(\cos\theta_r - \cos\theta_a)/\rho_L]^{1/4} \dots\dots\dots(18)$$

$$Q_L = 88.1A_s \text{ cm}^3/\text{s} \dots\dots\dots(19)$$

The increase in the coefficient from 4.5 to 5.9 is related to the roughness of the sliding gate wall. This equation is indicated by a solid line in Fig. 4.

4. Applicability of the Present Prediction Method to Real Sliding Gate

The advancing and receding contact angles are assumed to be equal to those shown in Eq. (16).⁸⁾ Substitution of $\theta_a = 120^\circ$, $\theta_r = 79^\circ$, $\sigma = 1700 \text{ mN/m}$, and $\rho_L = 7000 \text{ kg/m}^3$ into Eq. (18) yields

$$Q_L = 119A_s \text{ (cm}^3/\text{s)} \dots\dots\dots(20)$$

Fig. 2. Condition for attachment of bubble (non-coating).

Fig. 3. Condition for attachment of bubble (repellent 1).

Fig. 4. Condition for attachment of bubble (repellent 2).

When the diameter of immersion nozzle, D , is 10 cm and $A_s = 3A/4$, Eq. (20) yields

$$Q_w = 420 \text{ (L/min)} \dots\dots\dots(21)$$

As a typical example, we consider the case that the di-

mensions of the mold are 280 mm×1 500 mm and the casting speed is 1.6 m/min in the real continuous casting process. The flow rate of molten steel is 672 L/min under this condition. This critical flow rate is equivalent to the critical value of 420 L/min. The present result suggests that argon gas attachment to the sliding gate is a usual event in the real immersion nozzle.

5. Conclusion

A semi-empirical equation was proposed for predicting the critical condition for argon gas attachment to the sliding gate in the immersion nozzle of the continuous casting process. The adequacy of this method was partly verified from water model experiments. The predicted result for molten steel flow suggests a possibility of argon gas attachment to the sliding gate in the real immersion nozzle.

Nomenclature

- A : Cross-sectional area of immersion nozzle
- A_s : Opening area of sliding gate
- b : Displacement of sliding gate
- D : Diameter of immersion nozzle
- g : Acceleration due to gravity

- j_g, j_L : Superficial velocities of gas and liquid, respectively
- Q_g, Q_L : Gas and liquid flow rates passing through immersion nozzle, respectively
- R : Radius of immersion nozzle
- θ_a, θ_r : Advancing and receding contact angles, respectively
- ρ_L : Density of liquid
- σ : Surface tension of liquid

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