Cold Model Study of the Effects of Density Difference and Blockage Factor on Mold Powder Entrainment

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Cold model experiments were carried out to understand the effects of the density difference between mold powder and molten steel and of the blockage factor for the immersion nozzle on the mold powder entrapment in the continuous casting mold. Water, salt water, fluorinert, and mercury were used as the working fluids. A seesaw type vessel was used as a model for the mold and it was inclined for generating an uneven flow approaching the immersion nozzle of poor wettability. The meniscus descended along the outer surface of the immersion nozzle due to a pressure difference induced along the immersion nozzle. The pressure difference was caused through an effect of abrupt arrival of the uneven flow. The penetration depth of the meniscus is closely associated with the mold powder entrapment at the nozzle ports. An empirical equation was proposed for the penetration depth. An increase in the blockage factor promoted the penetration of the meniscus.

KEY WORDS: continuous casting; mold powder; mold powder entrapment; immersion nozzle.

1. Introduction

Entrapment of mold powder into molten steel contained in the continuous casting mold is still a serious problem for producing clean steel.1–3) According to previous studies,4–10) the mechanism of mold powder entrapment can be classified into five types, as schematically shown in Fig. 1.

(1) Steady mold powder entrapment caused by steady reversing flow from the narrow face
(2) Mold powder entrapment caused by Karman’s vortex formed behind the immersion nozzle
(3) Mold powder entrapment caused by attack of rising large argon bubbles onto the meniscus
(4) Unsteady mold powder entrapment caused by abrupt arrival of reversing flow from the narrow face
(5) Unsteady mold powder entrapment caused by pressure difference induced in the longitudinal direction along the immersion nozzle

The mechanisms (1), (2), (4), and (5) are caused by an uneven reversing meniscus flow from the narrow face. Further information on these mechanisms and related references are given in Refs. 3, 8) and 9).

Unfortunately, it is difficult at present to judge which mechanism is the most responsible for the mold powder entrapment in the real continuous casting mold. This is because nearly identical values of the critical molten steel flow velocity near the meniscus, called the critical meniscus velocity, were obtained from the previous investigations except for the mechanism (3). The present authors considered that the mechanism (5) is the most essential mechanism for the mold powder entrapment and carried out model experiments to prevent the entrapment.5–7) As a first step, water and silicone oil were chosen as the working fluids, and accordingly, the density ratio of the upper liquid to the lower liquid was greater than 0.85. This range does not include the real density ratio of approximately 0.5. A definite conclusion therefore was not obtained in the previous investigations.

In this model study further attention will be paid to the mechanism (5). The effect of the density ratio on the mold powder entrapment was investigated using water, salt water, fluorinert, and mercury as the working fluids. The density ratio varied from 0.07 to 0.55. This range covered the density ratio values encountered in the real continuous casting process. In addition, the effect of the blockage factor on the mold powder entrapment was mentioned. The blockage fac-
tor was defined as the ratio of the outer diameter of the immersion nozzle to the length of the narrow face.

2. Experiment

2.1. Experimental Apparatus

Two combinations of the upper and lower liquids were chosen. One is a salt water and fluorinert system and the other is a water and mercury system. Figure 2 shows a schematic diagram of the experimental apparatus. An acrylic vessel and a stainless steel vessel were used for the salt water and fluorinert system and the water and mercury system, respectively. The thickness, \( B \), width, \( W \), and length, \( L \), of the acrylic vessel were 0.10 m, 1.00 m, and 0.20 m, respectively. The corresponding values of the stainless steel vessel were 0.05 m, 0.80 m, and 0.10 m, respectively. One of the vessels was settled on a seesaw type frame. The frame was inclined with an air cylinder at a constant angular speed, \( \Omega_r \), of 2.7, 3.8, and 18.7 deg./s for the salt water and fluorinert system and 3.0 and 4.3 deg./s for the water and mercury system. The inclination angle, \( \theta \), was 10 and 20 deg. for the salt water and fluorinert system and 5 and 10 deg. for the water and mercury system. A circular cylinder made of aluminum was placed on the center of the former vessel. The diameter of the cylinder was 0.02 m, 0.03 m, and 0.04 m. The blockage factor, \( D/B \), ranged from 0.2 to 0.4. An acrylic resin cylinder was used as the immersion nozzle for the latter vessel. Its diameter was 0.02 m and 0.03 m. The blockage factor was 0.4 and 0.6. The volumes of the upper and lower liquids were the same in each vessel.

2.2. Measurement Method of Liquid Flow Velocity around Immersion Nozzle

Seeding particles of a density of 1 000 kg/m\(^3\) and a mean diameter of 200 \( \mu \)m were mixed in the upper water layer. On the other hand, seeding particles of a density of 1 030 kg/m\(^3\) and a mean diameter of 100 \( \mu \)m were mixed in the upper salt water layer. The velocity of the upper liquid flow, \( V_1 \), was determined with particle image velocimetry (PIV). The velocity of the lower liquid, \( V_2 \), was calculated from the relationship that the flow rate of the upper liquid in the right direction is identical to that of the lower liquid in the left direction. According to the previous investigation,\(^7\) when the kinematic viscosities of the upper and lower liquids were less than 10 mm\(^2\)/s, the two liquids moved almost uniformly in the opposite directions. In other words, \( V_1 \) was nearly equal to \( V_2 \).

2.3. Measurement Method of Penetration Depth of Meniscus

Concerning the salt water and fluorinert system, it is easy to observe the meniscus because the two liquids are transparent and the vessel also is made of transparent acrylic resin. The motion of the meniscus around the cylinder was observed with a CCD camera and recorded on a personal computer. On the other hand, the vessel for the water and mercury system was made of stainless steel. The inner walls of the vessel were coated with acrylic resin to prevent chemical reactions with mercury. A window made of transparent acrylic resin was attached to one of the sidewalls for observing the deformation of the meniscus. A mirror was settled in the immersion nozzle made of transparent acrylic resin, as shown in the lower part of Fig. 3. The displacement of the meniscus was observed with a CCD camera and the penetration depth of the meniscus was determined.

2.4. Physical Properties of Liquids

Table 1 shows the physical properties of liquids at 298 K. Table 2 shows the density ratio of the upper and lower liquids and interfacial tension for the two combinations of liq-
uids. The density ratio in the real system is very close to the value for the salt water and fluorinert system. The interfacial tension values mentioned in this study are much smaller than that in the real system (approximately 1400 mN/m). The water and mercury system is the worst scenario for the mold powder entrapment because the density ratio of 0.07 is much smaller than that of the real system.

2.5. Contact Angle

Table 3 shows the contact angle values for the two systems. The aluminum cylinder is poorly wetted by fluorinert as the contact angle, $\theta_c$, of 156 deg. is much greater than 90 deg. The acrylic cylinder is also poorly wetted by mercury, as $\theta_c$ is 143 deg.

3. Experimental Results and Discussion

3.1. Deformation of Meniscus around Immersion Nozzle and Velocity Vectors of Approaching Flow

Figure 4 shows the deformation of the meniscus between water and mercury and the velocity vectors in the upper water layer, where $\Omega = 4.3$ deg./s and $\theta = 10^\circ$. The diameter of the cylinder, $D$, was 0.03 m. The upper liquid moved right, while the lower liquid moved left. It is evident that the velocity of water flow, $V_1$, is nearly uniform in the vertical direction. Accordingly, the mercury is assumed to move at the identical velocity in the left direction ($V_1 = V_2$) because the kinematic viscosity of mercury is much smaller than that of water.

Figure 5 shows the top and side views of the meniscus recorded with the CCD camera. The meniscus moved downward along the left hand side of the cylinder of a diameter of 0.03 m. Figure 6 shows the magnified images of the meniscus between the water and mercury. The minimum scale of the measure is 1 mm. The penetration depth of the meniscus was determined from these images.

3.2. Penetration Depth of Meniscus along Immersion Nozzle

The flow field around the cylinder can be schematically shown in Fig. 7. The direction of flow in each layer was represented by an arrow, where $V$ is the velocity of flow, $P$ is the pressure on the left hand side of the cylinder, $p$ is the density of liquid, $A$ is the area of descended meniscus, $H_{sl}$ is the penetration depth of the meniscus along the cylinder of good wettability. $^5$ The subscripts 1 and 2 denote the upper and lower liquids, respectively.
The pressure difference, $\Delta P (=P_1-P_2)$, is induced by an abrupt arrival of the upper and lower liquid flows to the cylinder. By considering a balance of the gravitational force and the buoyancy force, the following equation can be obtained.7,8)

$$\Delta P = \rho_1 g H_{ag} = \rho_2 g H_{ag}$$

where $g$ is the acceleration due to gravity. The pressure difference is given by

$$\Delta P = \frac{\rho_1 V_1^2}{2} + 2.5 \frac{\rho_2 V_2^2}{2}$$

Combination of Eqs. (1) and (2) yields

$$H_{ag} = (\rho_1 V_1^2 + 2.5 \rho_2 V_2^2)/(2g(\rho_2 - \rho_1))$$

The maximum penetration depth for a cylinder of good wettability appeared at a position slightly apart from the cylinder. The distance from the nozzle to that position was denoted by $L_b$. This distance was chosen for correlating penetration depth just as in the previous study.7) The measured values of $L_b/D$ can be satisfactorily correlated by the following empirical equation.

$$L_b/D = Fr^{0.7}$$

where $Fr$ is the modified Froude number.

### 3.3. Penetration Depth of Meniscus

The measured values of the penetration depth for a poorly wetted cylinder was represented by $H_{ap,mea}$, where the subscripts p and mea denote the poor wettability and measured value, respectively. The value of $H_{ap,mea}$ was divided by $H_{ag}$ and plotted against $D/L_b$ in Figs. 8(a) and 8(b). The solid lines in Figs. 8 denote the upper limit of the penetration depth of the meniscus determined in the previous study for silicone oil and water system.8) The subscript, ul, denotes the upper limit. The solid line was originally determined for a blockage factor, $D/B$, between 0.2 and 0.4 and a density ratio, $\rho_1/\rho_2$, greater than 0.85. The measured values of the upper limit for the salt water and fluorinert system ($D/B=0.3$ and 0.4) were located beneath the solid line. The identical result was obtained for the water and mercury system, $\rho_1/\rho_2=0.07$, when the blockage factor was 0.4. These results collectively suggest that the penetration depth of the meniscus along the outer surface of the immersion nozzle is independent of the density ratio, $\rho_1/\rho_2$.

In Fig. 8(b) the penetration depth of the meniscus increased when the blockage factor, $D/B$, increased from 0.4 to 0.6. The increment was approximately 50%. This is because the pressure drop on the left hand side of the cylinder, $\Delta P$, significantly increased with an increase in $D/B$. In the real continuous casting process the blockage factor ranges from approximately 0.3 to 0.6. Accordingly, the data in Fig. 8(b) is applicable to the real process.

The solid line in Fig. 9 represents the upper limit of the penetration depth, being expressed by

$$H_{ap,ul} = 3.8 H_{ag}$$

$$= 3.8(\rho_1 V_1^2 + 2.5 \rho_2 V_2^2)/(2g(\rho_2 - \rho_1))$$

In the real continuous casting process the velocity of mold powder flow is very low compared to the meniscus velocity of molten steel flow, and accordingly, the mold powder is assumed to be stationary. Substitution of $V_1=0$ into Eq. (6) yields

$$H_{ap,ul} = 4.8 \rho_2 V_2^2/(g(\rho_2 - \rho_1))$$
3.4. Case Study

We consider a case of \( B/0.25 \text{ m} \) and \( D/H = 0.15 \text{ m} \) (\( D/B = 0.6 \)), as shown in Fig. 10. The distance from the ports of the immersion nozzle to the meniscus is assumed to be 0.15 m. Substituting \( H_{ap,ul} = 0.15 \text{ m} \), \( r_2 = 7000 \text{ kg/m}^3 \), and \( (r_2 - r_1) = 4000 \text{ kg/m}^3 \) into Eq. (7) yields

\[
V_2 = 0.42 \text{ m/s} \tag{8}
\]

According to the previous investigations, under this condition the critical value of \( V_2 = 0.76 \text{ m/s}, 0.86 \text{ m/s}, \) and \( 0.66 \text{ m/s} \) for the mechanisms (1), (2), and (4), respectively. The critical meniscus velocity estimated in this study is the lowest. As far as the critical meniscus flow is concerned, the mechanism (5) is the most appropriate for estimating the occurrence of mold powder entrapment.

4. Conclusions

Mold powder descended along the outer surface of the immersion nozzle due to pressure difference caused by abrupt arrival of uneven reversing flow from the narrow face. The penetration depth of the meniscus between the mold powder and the molten steel was investigated based on cold model experiments. The density ratio was significantly decreased compared to the previous cold model experiments. This density ratio includes the value encountered in the real process. When the blockage factor was less than 0.4, the previously derived empirical equation for the penetration depth was applicable regardless of the density ratio. The density ratio therefore was not dependent on the penetration depth.

When the blockage factor was elevated from 0.4 to 0.6, the increment of the penetration depth was 50%. As the blockage factor ranges from approximately 0.4 to 0.6 in the real process, the presently obtained relationship, Eq. (7), would be applicable to the real process. As far as the critical meniscus velocity is concerned, the mechanism (5) is the most appropriate for estimating the occurrence of mold powder entrapment.

Nomenclature

- \( B, W, L \): Thickness, width, and length of model vessel, respectively (m)
- \( D \): Outer diameter of immersion nozzle (m)
- \( Fr \): Modified Froude number (–)
- \( g \): Acceleration due to gravity (m/s²)
- \( H_{ag} \): Penetration depth of meniscus along immersion nozzle of good wettability (m)
- \( H_{ap,ul} \): Upper limit of penetration depth for immersion nozzle of poor wettability (m)
- \( L_b \): Distance (m)
- \( V_1, V_2 \): Velocities of the upper and lower liquids, respectively (m/s)
- \( \theta \): Inclination angle (deg.)
- \( \theta_c \): Contact angle (deg.)
- \( \rho_1, \rho_2 \): Densities of the upper and lower liquids, respectively (kg/m³)
- \( \Omega_r \): Angular speed of vessel rotation (deg./s)

REFERENCES