Effect of Electromagnetic Brake on Decreasing Unbalanced Flow in Mold

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Abstract. In order to clarify the mechanism of suppression of unbalanced flow in the mold under high throughput conditions in continuous casting, the effect of using an electromagnetic brake on decreasing molten steel momentum and suppressing unbalanced flow in the mold was investigated. (1) The measured value of the effect of the electromagnetic brake on decreasing molten steel momentum was consistent with the calculated value. Molten steel momentum could be reduced by more than 50% when the Stuart number was more than 3.5. (2) Increased mold level fluctuations caused by unbalanced flow in the mold are suppressed by applying the optimum magnetic flux density with an electromagnetic brake, even under high throughput conditions.

1. Introduction
Inclusions and bubbles which are trapped by the solidified shell during continuous casting and remain in the slab can cause defects during cold or hot rolling. In recent years, higher surface quality has been required under high throughput conditions in continuous casting.

High throughput conditions in continuous casting induce penetration of inclusions into the deep region and entrainment of mold flux caused by increased mold level fluctuations, and thereby degrade the quality of slabs. However, it is possible to reduce penetration of inclusions into the deep region and suppress mold level fluctuations by applying an electromagnetic brake in the mold. It is also known that an unbalanced flow is induced by nozzle clogging or sliding nozzle gate movement, and this unbalanced flow increases under high throughput conditions. When a large unbalanced flow occurs in the mold, areas of large or small molten steel flow velocity in the mold occur (Fig.1).
In a large upward flow velocity area at near the narrow side of the mold, mold flux entrainment is caused by the large mold level fluctuations at the meniscus of the mold\(^9\). In the deeper region of the mold, penetration of inclusions is caused by the large downward flow velocity\(^{10}\). In a small molten steel flow velocity area at the inner shell, entrapment of inclusions and/or bubbles at the solid–liquid interface increases due to the decrease of washing effects\(^{11}\). If the unbalanced flow in the mold is large, it may also cause breakout due to remelting of the solidified shell at the narrow side area by the large discharge flow rate from the submerged entry nozzle (SEN)\(^{12}\). As techniques for suppressing unbalanced flow in the mold, study of the shape of the immersion nozzle, electromagnetic stirring in the mold, and application of an electromagnetic brake to the immersion nozzle have been reported\(^{13-15}\). However, the relationship between unbalanced flow in the mold and the distribution of defects entrapped on the solidified shell in the mold, and the effect of an electromagnetic brake in the mold on unbalanced flow had not been investigated. In this paper, we measured the molten steel momentum in a mold that has two static magnetic fields in the upper and lower areas of the mold and the distribution of defects entrapped on the solidified shell in order to evaluate the effects of the electromagnetic brake on the distribution of defects entrapped on the solidified shell, unbalanced flow and the molten steel momentum in the mold.

2. Experimental

Experiments were performed at No. 3 continuous caster (No. 3 CC) at JFE Steel East Japan Works (Chiba District), where the strand is equipped with the electromagnetic FC (Flow Control) mold\(^3\). A schematic diagram of the FC mold is shown in Fig. 2.

Fig. 2 FC mold\(^3\).

The FC mold uses two static magnetic fields, an upper field at the slab meniscus level to control the meniscus metal flow velocity, and a lower field to control the lower part of the mold in order to minimize the penetration depth of the steel jets from the SEN(Fig.3)\(^8\).

Fig. 3 Flow velocity vector with 0.3 T magnetic field using FC mold\(^8\).
In the FC mold, the discharge holes of the SEN are located between the center of upper magnetic field and the center of the lower magnetic field. In this experiment, a three-layer type sliding gate was used. The opening and closing direction is the mold width direction. Casting was performed while blowing Ar gas through the SEN (two hole-type pool bottom nozzle). The experimental conditions are listed in Table 1. The casting speed was from 1.2 m/min to 1.7 m/min, and the maximum throughput was 5.3 ton/min. During the test, the magnetic flux density of the electromagnetic brake in the FC mold was varied under various casting conditions. The concentration of C was varied from 0.0015wt% to 0.0018wt%. Ar gas was blown into the mold through the SEN. To evaluate the molten steel momentum reduction effect of the electromagnetic brake, the angles of dendrites in the slabs were measured, and the flow velocity of the molten steel in the mold was calculated using Eq. (1)\(^9\).

To evaluate the solidification constant (\(2.58 \times 10^{-2} \text{ m/s}^{1/2}\)) calculated by Eq. (2), iron-sulfur alloys were added to the molten steel during casting, and the solidified shell thickness in the slabs was measured with the sulfur concentrations. The solidification rates in Eq. (1) were calculated by Eq. (3). To measure the upward molten steel velocity, samples were cut from the short side of the slabs. After the samples were polished and etched with picric acid, the angles of dendrites were measured at 1mm intervals by using a microscope.

\[
\theta = \frac{0.35 \cdot C_0^2}{C_0^2 + 0.0005} + 0.65 \cdot 11.5 \cdot V_F^{-0.177} \cdot \log \left( \frac{5.38 \cdot 10^{-3} \cdot V_F^{2.08}}{V} \right) 
\]  
(1)

\[
D = K \sqrt{t} = K \sqrt{z/V_c} 
\]  
(2)

\[
V = \frac{dD}{dt} 
\]  
(3)

Where, \(\theta\): angles of dendrites [degree], \(V_F\): molten steel flow velocity [m/s], \(V\): growth rate [m/s], \(C_0\): carbon content in molten steel [mass%], \(D\): solidified shell thickness [m], \(K\): solidification constant [m/s\(^{1/2}\)], \(t\): time [s], \(Z\): distance from meniscus [m] and \(V_c\): casting velocity [m/min].

3. Calculation Method

The molten steel flows in the mold were calculated in order to evaluate the effect of the electromagnetic brake\(^{11}\). The standard k-\(\varepsilon\) model in Fluent was employed to calculate the molten steel flows in the mold\(^{17-18}\). The equation of continuity, Navier-Stokes equation and law of the conservation of energy in Fluent are expressed by Eqs. (4)-(6).

\[
\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0 
\]  
(4)

\[
\rho \left[ \frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla) \vec{v} \right] = -\nabla p + \eta \nabla^2 \vec{v} + \vec{F} 
\]  
(5)

\[
\rho \left[ \frac{\partial \vec{T}}{\partial t} + (\vec{v} \cdot \nabla) \vec{T} \right] = \frac{k}{C_p} \nabla^2 T + \frac{Q}{C_p^2} 
\]  
(6)

Where, \(\vec{v}\): velocity [m/s], \(\rho\): molten steel density, \(p\): pressure [Pa], \(\eta\): viscosity coefficient [0.0057Pa·s]\(^{19}\), \(\vec{F}\): external force [N/m\(^3\)], \(T\): temperature [K], \(k\): thermal conductivity [34W/K/m]\(^{20}\), \(C_p\): specific heat at constant pressure [7533J/kg/K]\(^{21}\), \(Q\): latent heat flux of solidification [J/m\(^3\)/s], \(x\): width direction in mold, \(y\): thickness direction in mold and \(z\): continuous casting direction.

We calculated the solid phase ratio was calculated from the temperature field. \(Q\) was calculated by coupling the flow calculations with a subroutine of a changing coefficient of viscosity. The electromagnetic braking forces were calculated by using Eqs. (7)-(8) while determining external magnetic field \(B\).
\[ J = \sigma(E + V + B) = \frac{1}{\mu} \nabla \times B \quad (7) \]

\[ \frac{\partial B}{\partial t} + (\nabla \cdot B) = \frac{1}{\sigma \mu} \nabla^2 B + (B \cdot \nabla) V \quad (8) \]

Where, \( J \): electric current density \([A/m^2]\), \( E \): electric field \([V/m]\), magnetic flux density \([T]\), \( \sigma \): electric conductivity \([7.14 \times 10^6 S/m]\)⑵, and \( \mu \): magnetic permeability \([1.26 \times 10^{-6} H/m]\)⑷.

4. Experimental Results and Discussion

4.1. Effect of electromagnetic brake on molten steel momentum

Fig. 4 shows the relationship between magnetic flux density and decreasing ratio of molten steel momentum in the mold. The vertical axis is the ratio of measured or calculated molten steel momentum to momentum without magnetic field. The measured molten steel momentum \( \rho V_m \) was determined from the angles of dendrites (Eq. (1)) and the calculated molten steel momentum \( \rho V_c \) was determined by calculation by Eqs. (4)-(6). \( \rho V_c \) is the momentum in absence of the magnetic field and was calculated by Eqs. (9)-(13)⑶. \( \gamma \), \( h_{TD} \), \( l_1 \), \( l_2 \), \( l_3 \), \( q \), \( a \), \( B' \), \( \phi \), and \( d \) (Eqs. (9)-(13)) depend on the experimental conditions.

\[ V_d = \gamma \sqrt{(1 - \zeta_3)(1 - \zeta_4)} \cdot 2g[c^2(h_{TD} + l_1 + l_2 + l_3)] \quad (9) \]

\[ c = 0.364q^{0.65} \quad (10) \]

\[ \zeta_3 = 1.1 \left(1 - \frac{a}{B'}\right)^2 \quad (11) \]

\[ \zeta_4 = 1.16 - 0.015\phi \quad (12) \]

\[ \rho V_c = \rho V_e \left(\frac{X}{6.3d}\right)^{-1} \quad (13) \]

Where, \( V_d \): discharge flow rate from submerged nozzle \([m/s]\), \( \gamma \): ratio of average flow velocity and maximum flow velocity from discharge portion of submerged nozzle⑶, \( g \): acceleration of gravity \([m/s^2]\), \( h_{TD} \): molten steel depth in tundish \([m]\), \( l_1 \): length of upper nozzle \([m]\), \( l_2 \): length of under nozzle \([m]\), \( l_3 \): distance between under nozzle and molten steel surface level in submerged nozzle \([m]\), \( c \): coefficient of discharge of free fall flow in submerged nozzle \([\cdot]\), \( q \): molten steel throughput \([\text{ton/min}]\), \( a \): cross-sectional area of falling flow in submerged nozzle \([m^2]\), \( B' \): cross-sectional area in submerged nozzle \([m^2]\), \( \phi \): discharge angle of submerged nozzle \([\text{degree}]\), \( V_e \): molten steel collision velocity on narrow side of mold \([m/s]\), \( X \): horizontal distance between discharge port of submerged nozzle and mold wall \([m]\) and \( d \): diameter of discharge port in submerged nozzle \([m]\).

When the magnetic flux density is small, the actual measured momentum value is equivalent to that in the absence of the influence of a magnetic field obtained by Eq. (13).

On the other hand, when the magnetic flux density is large, the actual measured momentum value is smaller, and it was confirmed to be about half of the maximum momentum compared with the case of not applying the magnetic brake. The calculation results of the molten steel momentum were in good agreement with the actual measured values at the molten steel throughput values of 4.7 and 5.4 ton/min. Electromagnetic braking force \( F \) in a mold can be expressed by Eq. (14).

\[ F = J \times B \quad (14) \]
Fig. 4 Relationship between magnetic flux density and $(q_{vm}/q_v)$ or $(q_{vc}/q_v)$.

Fig. 5 Calculation results of Lorentz force and flow velocity.

Fig. 5 shows the results of the calculated Lorentz force and the flow velocity in the mold under the magnetic flux density conditions of 0.07 and 0.27 T. The effect of the Lorentz force on the molten steel was increased by increasing the magnetic flux density. As a result, the momentum of the molten steel collision on the narrow sides of the mold was reduced. The Stuart number N was evaluated in order to investigate the effect of electromagnetic force. The Stuart number N is the ratio of inertial force and external force represented by Eq. (15)\(^2\).
\[ N = \left( \frac{\sigma (v \times B) \times B}{\rho (v \cdot \nabla) v} \right) = \frac{B^2 \sigma L}{\rho v} \]

(15)

Where, \( L \): characteristic length [m] \( \approx \) mold width [m]

Fig. 6 shows the relationship between \( N \) and the magnetic flux density under different throughput conditions. In order to increase the effect of the electromagnetic brake force and overcome inertial force under large throughput conditions, it is necessary to apply a larger magnetic flux density compared with the case of low throughput conditions. From this, it is important to apply an adequate electromagnetic brake corresponding to increased throughput conditions. Fig. 9 shows the relationship between \( N \) and the ratio of measured or calculated molten steel momentum in the mold to the momentum calculated by Eq. (13).

Fig. 6 Relationship between \( N \) and \((\rho v_m/\rho v_e)\) or \((\rho v_c/\rho v_e)\).

Fig. 7 Relationship between Stuart number \( N \) and mold level fluctuations.

A correlation can be observed between the ratio of the measured or calculated molten steel momentum in the mold and the momentum calculated by Eq. (13) and \( N \). The momentum reduction effect of the electromagnetic brake in the mold is large with large \( N \). Under the different throughput and magnetic flux density conditions, it is considered that the molten steel momentum in the mold can be reduced to about 50%, compared to that in case an electromagnetic brake is not applied, when \( N \) is more than 3.5.
4.2. Effect of electromagnetic brake on mold level fluctuations

Fig. 7 shows the relationship between N and increases in mold level fluctuations due to unbalanced flow in the mold under different magnetic flux density conditions. Mold level fluctuations decreases with increasing N. These results are the same as the results for the relationship between the difference of molten steel momentum and molten steel throughput in the mold. Based on these results, it can be stated that the unbalanced distribution of defects and increased mold level fluctuations caused by an unbalanced flow in the mold are suppressed by applying the optimum magnetic flux density with an electromagnetic brake, even under high throughput conditions.

5. Conclusion

The effect of using an electromagnetic brake on decreasing molten steel momentum and suppressing unbalanced flow in the mold was investigated. The following knowledge was obtained.

(1) The measured value of the effect of the electromagnetic brake on decreasing molten steel momentum was consistent with the calculated value. Molten steel momentum could be reduced by more than 50% when the Stuart number N was more than 3.5.

(2) Increased mold level fluctuations caused by unbalanced flow in the mold are suppressed by applying the optimum magnetic flux density with an electromagnetic brake, even under high throughput conditions.

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