Effect of Magnetic Field Conditions on the Electromagnetic Braking Efficiency

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Effect of different types of in-mold electromagnetic brake (EMBr) technique, which forms a local magnetic field and a level magnetic field in the width direction of a mold, on the fluid flow phenomena in the strand pool was examined. A mercury model experiment revealed that the level magnetic field developed a plug-like flow in the strand pool, of which flow could not be obtained by the local magnetic field. Surface velocity near the meniscus could be stably controlled with the level magnetic field, while in the case of the local magnetic field, this surface velocity was greatly affected by the nozzle condition. Numerical analysis clarified the characteristics in the distribution of an induced electric current density and Lorentz force, and explained the flow behavior with the local and level magnetic fields, respectively.

KEY WORDS: continuous casting; fluid flow; electromagnetic brake (EMBr); mercury model experiment; numerical analysis; magnetohydrodynamics (MHD).

1. Introduction

The steel flow discharged from the immersion nozzle in the continuous casting (CC) mold often entraps the mold flux at the meniscus and sends nonmetallic inclusions deep into the strand. The entrapped mold flux and dispersed nonmetallic inclusions become serious factors in the degradation of cast steel quality and hamper the progress in high-speed casting. To solve these problems, numerous techniques for applying an electromagnetic force to the continuous casting process have been developed.1) One of these techniques, the in-mold electromagnetic brake (EMBr) technique, was the first to utilize a local magnetic field as shown in Fig. 1(b), which acts directly on the molten steel discharged from the immersion nozzle to reduce its flow velocity.2–4) Nowadays, a level magnetic field in the width direction of a mold as shown in Fig. 1(a), is widely utilized for the sake of obtaining a more stable electromagnetic braking effect.5–7)

When a DC magnetic field is externally imposed on an electrically conductive fluid, electric current is induced in the fluid. The current induced in the flow system forms a path so that it satisfies the law of conservation of an electric current based on the electric boundary condition, fluid velocity distribution and magnetic flux density distribution. However, the effect of these magnetic field conditions on the electric current path and electromagnetic braking efficiency has not been fully clarified.

The objective of this study is to clarify the effect of different types of magnetic fields utilized in the EMBr technique, on the fluid flow behavior in the continuous casting strand. A mercury model experiment and the numerical analysis revealed the characteristics of fluid flow and electromagnetic field in the strand pool with the local and level magnetic fields, respectively.

2. Mercury Model Experiment

2.1. Experimental Apparatus

The apparatus used in the mercury model experiment is illustrated in Fig. 2. It is composed of a stainless steel vessel, a level controller, a tundish and a DC magnet. A mercury pool in the vessel, which is equivalent to the top of the strand pool in a continuous caster, is piped to the level controller. The meniscus level of the pool can be easily con-
trolled at a constant level, according to the principle of the U-shaped tube. The mercury then is pumped up into the tundish above the strand pool. From there, it is discharged again into the pool through a pipe, which serves as an immersion nozzle. In the lower part of nozzle, the acrylic pipe is utilized for electric insulation. The flow rate of the mercury through the immersion nozzle is adjusted by a stopper in the tundish.

Two types of DC magnets were placed around the vessel to investigate the effect of the magnetic field conditions on the flow. One DC magnet type forms a DC magnetic field partially crossing the broad face of the mold. The other one forms a level magnetic flux density in the width direction of the pool. The resulting flow of mercury then was used to predict the molten steel flow. The distribution of magnetic flux density which each DC magnet forms, was measured without mercury circulation. Figures 3(a) and 3(b) show the vertical and horizontal distribution of the magnetic flux density throughout the pool of mercury in the case of the local magnetic field and the level magnetic field, respectively.

2.2. Experimental Conditions

Table 1 gives the experimental conditions adopted in the mercury model experiment. The total amount of mercury in the pool was about 2 tons. The level magnetic field’s center was 155 mm below the meniscus. The local magnetic field’s center was 150 mm below the meniscus and 150 mm from the center of the pool. In addition, the effect of an angle of nozzle port, 15 degrees downward and 45 degrees downward respectively, on the fluid flow was examined. These experiments will be referred to as nozzle condition A and nozzle condition B, respectively, throughout the remainder of this paper.

Figure 4 shows the relationship between the discharged flow and DC magnet in each magnetic field condition. With the local magnetic field, the crossing length in the magnetic area is longer in the nozzle condition A than the one in the nozzle condition B. With the level magnetic field, in both of the nozzle conditions A and B, the discharged flow directly crosses the level magnetic field, which leads to better electromagnetic braking efficiency, as mentioned by Zeze.5)

The velocity of the mercury was measured with a sensor developed by Vives.6) Figure 5 shows the relationship between the mercury’s velocity and the output voltage of the sensor, which has been calibrated. The sensor uses a permanent magnet made of samarium-cobalt, which forms the magnetic field of 0.4 Tesla (T). The effect of placing an external magnetic field near the magnetic poles, where the magnetic field already was high in magnitude, could not be ignored. Hence, the velocity measurement was not conducted in the region of the pool where the magnetic flux density exceeded 0.2 T.

Similarities between the model and the continuous caster were maintained by the following Froude number and the Stuart number:

\[
\text{Fr} = \frac{U}{\sqrt{gL}} \quad \text{St} = \frac{\sigma B^2 L}{\rho U} \quad \text{(1)}
\]

The condition, in which the flow rate of mercury is 30 l/min, is equivalent to the one in which casting speed is 0.79 m/min. The imposition of magnetic field of 0.3 T to the

![Fig. 2. Experimental system for the mercury model experiment.](image)

![Fig. 3. Magnetic flux density distribution in the case of local and level magnetic fields (a) in the width direction of the pool and (b) in the vertical direction of the pool.](image)
mercury pool is equivalent to the one of magnetic field of 0.2 T to the molten steel pool.

2.3. Experimental Results

Figure 6 shows, for the nozzle condition B, how the local and level magnetic fields change the flow pattern. Without a magnetic field, the flow discharged from the nozzle impinges on the narrow face of the vessel and mainly forms a downward stream toward the pool. Near the meniscus, the fluid flow is stagnant. Meanwhile, the downward stream deeply penetrates along the narrow face of the vessel and forms a large circulating flow. The velocity of the downward stream is highest near the narrow face of the vessel and declines toward the center of the pool.

In the case of the local magnetic field with a flux density of 0.3 T, the discharged flow impinges on the narrow face and divides into upward stream and downward stream. The portion of the discharged flow easily penetrates between the imposed magnetic field area and the nozzle. On the contrary, the surface flow velocity with the local magnetic field is accelerated compared to that without a magnetic field.

By imposing a level magnetic field with a flux density of 0.3 T, the velocity distribution is greatly changed. The penetration of the discharged flow is prevented with the level magnetic field. As a result, the circulating flow pattern below the imposed magnetic field region disappears and the bulk of the mercury flows downward at an extremely low velocity. This velocity is almost equivalent to the mercury flow rate divided by the cross-sectional area of the pool. This implies that a plug-like flow develops below the level magnetic field. On the contrary, the surface flow velocity is accelerated compared to that without a magnetic field.

Figure 7 shows the effect of magnetic field conditions on the vertical velocity distribution in the width direction at 630 mm below the meniscus. Without a magnetic field, a
downward stream near the narrow face of the vessel and an upward stream in the center of the pool are observed and a large recirculating flow in the pool can be confirmed. With the local magnetic field, a portion of the discharged flow penetrates the front of the imposed magnetic field area and the vertical velocity distribution in the width direction does not become uniform. On the contrary, the vertical velocity distribution becomes almost uniform with the level magnetic field.

Figures 8(a) and 8(b) show, for both the local and level magnetic fields, the effect of the magnetic flux density and nozzle conditions on the velocity of the downward stream at a location 20 mm from the narrow face of the vessel and 630 mm below the meniscus. The vertical axis indicates the normalized velocity, which is the downward velocity divided by the plug-like flow velocity. Note that the velocity distribution of the downward flow becomes uniform if the normalized velocity is unity. We found that the normalized velocity decreases with the magnetic flux density increasing. In the case of the level magnetic field, the normalized velocity decreases markedly at over 0.3 T and the mercury stream comes to a plug-like flow at about 0.55 T.

Meanwhile, the surface velocity near the meniscus was also affected by the magnetic field conditions. Figures 9(a) and 9(b) show, for both the local and level magnetic fields, the effect of the magnetic flux density and nozzle conditions on the surface velocity at a quarter width of the pool and 30 mm below the meniscus. With the level magnetic field, the surface velocity attained its maximum value at a magnetic flux density of 0.2 T. When the magnetic flux density rose over 0.4 T, the surface velocity dropped to the value without the level magnetic field. On the other hand, the surface velocity was greatly affected by the nozzle conditions with the local magnetic field. In the nozzle condition A, the changes in the surface velocity with magnetic flux density is similar to the changes in the surface velocity with the level magnetic field. On the contrary, in the nozzle condition B, the surface velocity is only accelerated with
magnetic flux density. It is due to the difference of the crossing length of the discharged flow in the imposed magnetic field region.

3. Numerical Analysis

3.1. Numerical Model

The fluid behavior with the DC magnetic field was numerically calculated by using a numerical model developed by Sawada. The motion of liquid metal flow is described by the equations:

$$\nabla \cdot U = 0 \quad \text{(2)}$$

$$\frac{\partial U}{\partial t} + U \cdot \nabla U = \frac{\nabla P}{\rho} + \frac{F}{\rho} + \nabla \cdot \nu \nabla U \quad \text{(3)}$$

Large Eddy Simulation was adopted in this model in order to analyze the time-dependent fluid behavior.

Under the MHD approximation and the continuity of electric current, the electromagnetic field is described by the following equations:

$$E = - \nabla \phi \quad \text{(4)}$$

$$J = \sigma(E + U \times B) \quad \text{(5)}$$

$$\nabla \cdot J = 0 \quad \text{(6)}$$

$$F = J \times B \quad \text{(7)}$$

Equations (2)–(7) were solved simultaneously and as a result the flow field and electromagnetic field were calculated.

3.2. Numerical Conditions

Figure 10 shows the computational system. Table 2 gives numerical calculation conditions. The computational area of the analysis includes the stainless steel vessel, which corresponds to the solidified shell in the continuous casting process. Enough meshes in the nozzle were set in order to simulate the change in the angle of discharged flow with magnetic field and uniform velocity was set at the top in the nozzle. The wall function according to logarithmic law was employed at the inner face of the vessel and nozzle face. In this analysis, free surface deformation was not taken into account and the free-slip condition was employed at the surface of the mercury pool. The distribution of the magnetic field used for the calculation was given by the measured value, as shown in Fig. 3. Numerical calculation was iterated until 200 sec to examine the fluid behavior with DC magnetic field.

3.3. Numerical Results

For the nozzle condition B, the computed results of the velocity distribution without a magnetic field, with the local magnetic field of 0.3 T and with the level magnetic field of 0.3 T, are shown in parts (a), (b) and (c) of Fig. 11, respectively. Similar to the mercury model experiment, without a magnetic field, the discharged flow from the nozzle port impinges on the narrow face of the vessel and then forms large vortices in the pool. With the local magnetic field, the discharged flow from the nozzle is braked to impinge on the narrow face of the vessel and divide into an upward stream and downward stream in a stable manner. It can be seen that the angle of discharged flow shifts upward and downward stream forms below the nozzle. On the contrary, we can find some changes in the entire flow pattern in the pool with the level magnetic field. One change is that the angle of the discharged flow shifts upward and the discharged flow velocity is decelerated. A second change is that lower vortices are suppressed and an almost plug-like flow develops. Additionally, we can find that a counter flow forms around the discharged flow and this flow reaches to the meniscus along the nozzle.

Figure 12 shows the changes in the vertical velocity distribution in the width direction of the pool at 630 mm below the meniscus with the application of each DC magnet. It can be seen that downward stream near the narrow face and upward stream in the bulk pool are formed without magnetic field. With the local field, the downward stream is formed at the center of the pool. At the vicinity of narrow face, the velocity of downward stream is higher in the level field than the one in the local field.

About the downstream velocity near the narrow face and the surface flow velocity, the calculated results were compared with experimental ones. Figures 13(a) and 13(b) show the effect of magnetic field conditions on the normalized downstream velocity at 630 mm below the meniscus and 20 mm in the narrow face and on the surface flow velocity at a quarter width of the pool and 30 mm below the meniscus, respectively. It can be seen that the downstream velocity decreases with magnetic flux density in both cases and the calculated results show good agreements with the experimental ones.

On the other hand, the calculated results show that the surface flow velocity firstly increases and then drops to the
one without magnetic field in both cases, when the magnetic flux density increases. The acceleration of surface flow is due to the upward shift of the discharged flow as shown in Fig. 11. The deceleration of surface flow is mainly due to the braking of the discharged flow. In the case of level magnetic field, the braking of upward stream along the narrow face also leads to the deceleration of the surface flow velocity. In the case of local magnetic field, the tendency of the surface flow velocity with magnetic flux density observed in the calculated results is different from the one observed in the experimental results. We can observe this tendency in the nozzle condition A as shown in Fig. 9. Therefore, the difference of the angle of discharged flow might lead to the difference in the tendency of the surface flow velocity with the magnetic flux density.

In order to clarify the effect of the magnetic field conditions on the unbalanced meniscus flow at each narrow face, the difference of each upward velocity at a location 40 mm below the meniscus and 20 mm in the narrow face was calculated. Figure 14 shows the effect of the magnetic field conditions on the maximum value of the velocity difference in the period of 82 sec. It can be observed that in both magnetic fields, the velocity difference decreases with magnetic flux density and the effect is marked in the level magnetic field.

Figures 15(a) and 15(b) show the vector of current density at half thickness in the mercury pool with the local magnetic field and level magnetic field, respectively. With the local magnetic field, as the direction of magnetic field on the right hand side of the pool is opposite to that on the left hand side of the pool, the induced current path is limited within each side of the pool. On the contrary, in the case of the level field, the current path is formed around the nozzle. Moreover, the electric current is induced against the upward and downward flow near the narrow face of the vessel.
Figures 16(a) and 16(b) show the vector of current density around the nozzle with the local and level magnetic fields, respectively. With the level magnetic field, the induced current flows into the nozzle through the port and forms a path both around the nozzle and in the nozzle. On the contrary, with the local magnetic field, the electric current path is limited within the right and left hand sides of the pool, because the magnetic field partially imposed on the right hand side of the pool is opposite to that imposed on the left side of the pool. In addition, the electric current induced by the discharged flow forms an electric current paths around the jet to satisfy the continuity of current.

Figures 17(a) and 17(b) show the vector of the Lorentz force at half thickness in the pool with the local magnetic field and level magnetic field, respectively. With the local magnetic field, the Lorentz force partially acts because of the localized magnetic flux density distribution in the pool. We can additionally find that the Lorentz force acts to the direction of the nozzle port at the upper and the lower region of the discharged flow. This is due to a secondary induced electric current path. Moreover, this secondary electric current path is dependent on the velocity and magnetic field distribution, in other words, the relationship between the discharged flow and the DC magnet, and greatly affects the entire flow pattern. On the contrary, in the case of the level magnetic field, the braking force against the upward flow and downward flow near the narrow face of the vessel acts as well as the one against the discharged flow. The formation of the current path through the nozzle port has an additional effect, namely, it brakes the flow in the nozzle and it prevents an unbalanced flow. These differences in the electromagnetic field formed with each DC magnet leads to the difference in the electromagnetic braking efficiency.

4. Conclusions

A mercury model experiment and numerical analysis have been performed to examine the effect of different types of magnetic fields utilized in the EMBr technique, which form a local magnetic field and a level magnetic field in the width direction of the mold, on the liquid metal flow in the continuous casting strand. The results of this experiment and analysis are summarized as follows:

(1) The Flow Behavior with the Application of the Local and Level Magnetic Field

With the local magnetic field, the discharged flow from the nozzle easily penetrates between the nozzle and the imposed magnetic field area, and this field has less braking force than that of the level magnetic field to control the entire flow pattern because of the partial imposition of the magnetic field. Therefore, the braking efficiency is lower in the local magnetic field than that in the level magnetic field. A little difference in the nozzle conditions changes the crossing length of the discharged flow in the imposed magnetic field area, and as a result, this difference determines whether surface velocity is accelerated or decelerated. When a level magnetic field is imposed beneath the submerged entry nozzle in a mold, it brakes the flow of mercury from the nozzle in a stable manner. Also, the penetration depth of the downward flow into the pool decreases with the magnetic flux density increasing. Based on the results of the mercury model experiment and numerical
analysis, it can be predicted that the molten steel below the level magnetic field descends at the same speed as the withdrawal of the strand. Therefore, the level magnetic field develops a plug-like flow in the strand pool. An additional effect is that the velocity of the surface flow near the meniscus can be controlled by the level magnetic field.

(2) The Characteristics of the Electromagnetic Field Formed with the Local and Level Field

With the local magnetic field, the electric current path is limited within the right and left hand sides of the pool, because the magnetic field partially imposed on the right hand side of the pool is opposite to that imposed on the left hand side of the pool. In addition, the electric current induced by the discharged flow forms the electric current path in the neighborhood of the discharged flow to satisfy the continuity of the current and Lorentz force acts to the nozzle port. Moreover, the changes in the relationship between the discharged flow and the DC magnet affects the path of the electric current and the secondary flow around the discharged flow, as a result leading to a change in the entire flow pattern.

In the case of the level magnetic field, the electric current path is formed in the entire pool. As a result, the upward flow and downward flow near the narrow face of the vessel as well as the discharged flow from the nozzle can be
braked, thus making the plug-like flow beneath the magnet and control of surface velocity near the meniscus possible. By imposition of the level magnetic field beneath the nozzle port, the induced current is made to flow into the nozzle through the port and forms a path both around the nozzle and in the nozzle. The formation of the current path through the nozzle port has an additional effect, namely, it brakes the flow in the nozzle and it prevents an unbalanced flow.

Nomenclature

\[ \begin{align*}
B & : \text{Magnetic flux density (T)} \\
F & : \text{Lorentz force (N/m}^3) \\
Fr & : \text{Froude number (–)} \\
J & : \text{Current density (A/m}^2) \\
L & : \text{Characteristic length (m)} \\
P & : \text{Pressure (Pa)} \\
St & : \text{Stuart number (–)} \\
\tau & : \text{Time (sec)} \\
U & : \text{Velocity (m/s)} \\
\phi & : \text{Electric potential (V)} \\
v & : \text{Kinematic viscosity (m}^2\text{/s)} \\
\rho & : \text{Density (kg/m}^3) \\
\sigma & : \text{Electric conductivity (S/m)}
\end{align*} \]

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