Fluid Flow in a Continuous Casting Mold Driven by Linear Induction Motors

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Numerical flow analyses are performed to clarify the characteristics of a molten steel flow in the continuous casting mold using the electromagnetic stirring. The usage and variables of the linear induction motor in electromagnetic stirring are noted in the analysis. Uniformity of the circulating flow velocity is examined quantitatively. Especially, influences of the installed level of the linear induction motor which is one of the most important usage of the linear induction motor, and the pole number, which is one of the most important linear induction motor variables, on the molten steel flow are introduced.

KEY WORDS: continuous casting process; electromagnetic technique; numerical simulation; linear induction motor.

1. Introduction

In the continuous casting process, the method of improving the slab quality is an ongoing problem. The fluid flow of molten steel in a strand pool is one element which influences the slab quality. Modifications of the jet flow angle1,2) and remaking of the submerged nozzle shape3,4) have already been tried in order to control the fluid flow. In recent years, an electromagnetic technique, which is able to control fluid flow without contact between the liquid and technical tool has been used as a flow control technique.

There are two types of electromagnetic technique, electromagnetic brake (EMBr),5) which brakes the molten steel flow under a static magnetic field, and electromagnetic stirring (EMS),6) which generate a fluid flow by the Lorenz force provided by a linear induction motor. Effects for both types of techniques has been reported. EMBr decreases the oscillation mark depth and its dispersion.7) On the other hand, EMS decreases inclusion entrapments8,9) and longitudinal cracks.10)

Along with these reports, there have been many reports on numerical flow analysis. EMBr is classified into several methods by the region in which the static magnetic field is applied. Results from the numerical flow analyses in which a magnetic field is applied around the jet flow area11) and in the area for one or two certain depths and over the whole width12,13) have been reported. On the other hand, EMS is also classified into several methods by the direction of the Lorenz force and the region in which the Lorenz force is applied. The results of the numerical flow analysis for these methods in which the Lorenz force is in the direction of positive and negative jet flow accelerations,14) up and down directions,15) and a circulating direction16) have also been reported.

However, the numerical analyses in most report are performed for fluid flow only in standard conditions of machines using each electromagnetic methods. Although there are some results for comparing two different methods,17) the influence of variation of the machine application on fluid flow has rarely been reported. Especially in EMS, there are few reports about the influence of the positions of the machine18) and no report about the linear induction motor variables on fluid flow.

In this report, one type of EMS, which applies a Lorenz force in the circulating direction along the mold, is described. In this method, the uniformity of the circulating flow along the mold is important. When the circulating flow is uniform, the effect decreasing the inclusion entrapment can be obtained in the whole region along the mold circumference. In the paper, the index for the uniformity of the circulating flow is introduced. Influences of the position of the linear induction motor and of the pole number, which is the most important linear induction motor conditions for fluid flow, are also introduced using the index for the circulating flow derived from the numerical flow analysis.

2. Numerical Method

The governing equations used in the analysis are the conservation of mass and momentum as follows:

\[ 0 = \nabla \cdot u \] .................................................. (1)

\[ \frac{\partial u}{\partial t} + u \cdot \nabla u = - \frac{1}{\rho} \nabla P + \nu \nabla^2 u + F \] .................................. (2)
where \( u, t, P, \rho, v \) and \( F \) are the fluid velocity, time, pressure, density, kinetic viscosity and external force, respectively. LES\(^{(9)}\) and the Deardroff–Smagorinsky type\(^{(20,21)}\) of SGS are used as the turbulent model. FDM is used as discrete equations for partial differentiation. The combination of these methods in this analysis is generally used.\(^{(22)}\)

The external force \( F \) indicates the Lorenz force in the analysis. The Lorenz force has been derived from the other electromagnetic numerical analyses\(^{(23)}\) previously performed. Although the Lorenz force usually changes with time, the time-averaged Lorenz force is used in the analysis for good convergence. Thus the time-average flow velocity of more than 3 min, as the results of the numerical analysis, is used to discuss.

3. Validation of the Numerical Model

3.1. Numerical and Experimental Conditions

A numerical flow analysis for a continuous casting mold which has almost the same size and shape that the model experiment using a low melting metal has been carried out and the results for the numerical analysis and the model experiment are compared. Figure 1 shows the experimental apparatus and numerical region. Table 1 lists the experimental and numerical conditions. Technical words about the SEN in Table 1 are explained in Fig. 2. The shape of the SEN cross-section is square in the numerical analysis while it is a circle in the experiment. The outlet from the metal pool is a uniform downward velocity in the numerical analysis while it is one pipe in the experiment. Influences

![Fig. 1. Experimental apparatus and numerical region.](image1)

![Fig. 2. Technical words for submerged nozzle in Table 1.](image2)

| Table 1. | Experimental and numerical conditions. |
|----------|----------------------------------------|
| **metal** | \( \text{Bi-32\%P-16Sn} \) |
| **density** | \( 8800 \, \text{(Kg/m}^3) \) |
| **molden metal pool** |  |
| wide face | 2 (m) |
| narrow face | 0.25 (m) |
| depth | 1.95 (m) |
| taper | 0.0025 (m/m) (exp.) 0 (m/m) (calc.) |
| outlet | one pipe (exp.) level velocity (calc.) |
| **linear induction motor** |  |
| frequency | 3.3 (Hz) |
| electric current | 525 (A) |
| **submerged nozzle** |  |
| downward angle | 25 (deg) |
| shape | column (exp.) rectangle (calc.) |
| size | diameter (exp.) side (calc.) |
| outer | 0.150(m) 0.133(m) |
| inner | 0.085(m) 0.075(m) |
| depth of nozzle bottom | 0.34(m) |

![Fig. 3. Velocity distributions of jet flow at SEN port.](image3)
due to such differences between the experimental and numerical conditions on the results will be discussed later, in view of a comparison of the respective results. Incidentally, Vivés type sensor is used to measure the flow velocity in the experiment. The velocity distribution obtained by the measurements around the SEN port is used as a numerical analysis boundary condition for the inlet (Fig. 3).

3.2. Comparison between Numerical Analysis and Experiment

Figure 4 shows the velocity field on the horizontal cross-section near the meniscus and velocity profile along the wide face near the meniscus. It is clarified from Fig. 4 that almost the same flow patterns can be obtained both in the experiment and the numerical analysis. It is known from Fig. 5 that the experimental results of the velocity profile has a slight deviation, but that the numerical results of the velocity profile is a smooth line. It is considered that there are errors due to the measurement during the experiment and the possibility the small scale turbulence is not calculated in the numerical analysis. Although there are such differences between the experiment and the numerical analysis, it is found that the tendency and scale of the velocities almost agree.

Thus it is considered that the numerical method in the analysis has sufficient accuracy to allow the tendency of fluid flow to be discussed. Incidentally, because of the good agreement between the results of the experiment and the numerical analysis, it can be judged that no problem will arise if the influences of the differences between the experimental and the numerical conditions, the SEN shapes and the outlets, are ignored.

4. Fluid Flow Driven by Lorenz Force

4.1. Numerical Conditions

The numerical region is shown in Fig. 6. The numerical region is the molten steel pool with the linear induction motor at the upper part, which is a simple model of molten steel in the continuous casting mold with EMS. Linear induction motors are installed on both sides of the wide faces. The elements, for example, SEN and pull, which complicates the phenomenon, are submitted to clarify the characteristics of fluid flow driven by the Lorenz force. The size of the molten steel pool and specifications of the linear induction motor in this analysis are shown in Table 2.

The calculations are performed for linear induction motors with two different pole numbers and for two different installed levels of the linear induction motor for each pole number. Therefore, four sets of calculations are performed (Table 3).

The Lorenz force distributions used in the external force term are derived from the numerical electromagnetic analysis previously performed. Figure 7 shows the Lorenz force distributions in the 2- and 4-pole linear induction motors. It is well known that two and four vortexes are generated in the 2- and 4-pole linear induction motors respectively. We can also see the same pattern in Fig. 7.

4.2. Numerical Results

Eight velocity fields in both the 2- and 4-pole linear induction motors obtained as results of the numerical analysis are shown in Figs. 8 and 9, respectively.

4.3. Discussion

4.3.1. Influence of Installed Level of Linear Induction Motors on Fluid Flow

In both the 2- and 4-pole linear induction motors, it was
found from Fig. 8 and Fig. 9 that a circulating flow is generated in the central level of the linear induction motor and dissipate on the cross-section away from that. It can be said that this tendency is due to influence of the installed level of the linear induction motor on the fluid flow, because the flow pattern on the cross-section of a certain level is changed by the linear induction motor level. Index \( K \) is introduced to judge quantitatively whether the flow pattern is the circulating flow or not, before the mechanism is discussed. The definition of index \( K \) is as follows

\[
K = \frac{\int_{\text{near the outline of the molten steel pool}} u(x) \, dx}{\max(u(x)) \int_{\text{near the outline of the molten steel pool}} \, dx} \quad \text{............(3)}
\]

where \( u(x) \) is the flow velocity element of the molten steel parallel to the mold wall. The integration in Eq. (3) is performed on the line at 0.01 m inside the mold wall (see Fig. 10). \( K \) indicates uniformity of the flow velocity along the circumference of the molten steel pool. Absolute \( K \) is close to 1 when the flow velocity is close to uniform, while \( K \) is close to 0 when the flow velocity is not close to uniform. We can envision that the flow pattern is a circulating flow with absolute \( K \) being close to 1 and is not with absolute \( K \) being close to 0. Incidentally, the sign of \( K \) indicates the direction of rotation of the circulating flow which is counterclockwise for plus and clockwise for minus because the integration of Eq. (3) is performed in the counterclockwise direction.

The \( K \) depth distributions in the 2- and 4-pole linear induction motors are shown in Fig. 11 and Fig. 12 respectively. It is found from Fig. 11 and Fig. 12 that \( K \) is closest to 1 for the central linear induction motor level and approaches to 0 when away from the central level. This gives a quantitative explanation of the tendency of a circulating flow to be generated in the central level and dissipate when away from the central level.

The three-dimensional distribution of the fluid flow is considered to make the mechanism easier to understand. Distributions of the Lorenz force at depths in the 2- and 4-pole linear motors are shown in Fig. 13 and Fig. 14. It is found from Fig. 13 and Fig. 14 that the Lorenz force reaches a maximum in the central level of the linear induction motor. This shows that the flow pattern is significantly influenced by the Lorenz force generated in the central level of the linear induction motor. Thus the fluid flow in the central level of the linear induction motor often influences the upper and lower region but the fluid flow in the upper and lower regions rarely influences the central level region.

On the other hand, the distributions of the Lorenz force at the central level of the linear induction motor have two vortices in the 2-pole linear induction motor and four vortices in the 4-pole linear induction motor, as shown in Fig. 7. The ratio of the Lorenz force in the thickness direction along the thickness center to the Lorenz force parallel to the wide face along the wide face, which is the definition of \( L \) (see Fig. 15), is shown in Fig. 16. It is found from Fig. 16 that \( L \) is less than 1 in almost all regions, which means that the Lorenz force parallel to the wide face along the wide face is greater than that in the thickness direction at the central level of the linear induction motor and that it is easier for the circulating flow to flow along the wide face than to go across the thickness center line. Therefore it can be understood that one big circulating flow along the outline of

![Fig. 6. Numerical region.](image)

**Table 2.** Size of molten steel pool and specifications of linear induction motor.

| molten steel pool | linear induction motor |
|-------------------|------------------------|
| wide face         | frequency              |
| 1.61(m)           | 20(Hz)                 |
| narrow face       | electric current       |
| 0.25(m)           | 400(A)                 |
| depth             | slot number            |
| 6.13(m)           | 24                     |

**Table 3.** Numerical conditions.

| central level of linear induction motor | pole number |
|----------------------------------------|-------------|
| case.1                                 | 2           |
| 150 mm under meniscus                  |             |
| case.2                                 | 2           |
| 408 mm under meniscus                  |             |
| case.3                                 | 4           |
| 150 mm under meniscus                  |             |
| case.4                                 | 4           |
| 408 mm under meniscus                  |             |

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854
The molten steel pool is generated at the central level of the linear induction motor.

The velocity fields near the wide and narrow faces in case 4 are shown in Fig. 17 as an example. It is found from Fig. 17 that the circulating flow at the central level of the linear induction motor hits the wide and narrow faces and then radially spread out on the wide and narrow faces. Because the radially spread out flow disturbs the circulating flow to the upper and lower levels, it can be understood that uniformity of the velocity along the outline of the molten steel pool is dissipated on the cross-section away from the central level of the linear induction motor.

It was found from the above results that the installed level of the linear induction motor significantly influences a circulating flow and the uniformity of velocity along the outline of the molten steel pool.

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### Fig. 8. Velocity fields on the horizontal cross-section in 2-pole linear induction motor.

| Case   | Left Side | Right Side |
|--------|-----------|------------|
| Meniscus | ![](image1) | ![](image2) |
| 150mm under meniscus | ![](image3) | ![](image4) |
| 408mm under meniscus | ![](image5) | ![](image6) |
| 600mm under meniscus | ![](image7) | ![](image8) |

### Fig. 9. Velocity fields on the horizontal cross-section in 4-pole linear induction motor.

| Case   | Left Side | Right Side |
|--------|-----------|------------|
| Meniscus | ![](image9) | ![](image10) |
| 150mm under meniscus | ![](image11) | ![](image12) |
| 408mm under meniscus | ![](image13) | ![](image14) |
| 600mm under meniscus | ![](image15) | ![](image16) |

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![Fig. 10. Integral path of K.](image17)
4.3.2. Influence of Pole Number on Fluid Flow

The pole number is noted here as an example of the linear induction motor variables. The influence of the pole number on the circulating flow is also discussed.

A comparison of the $K$ distributions in the 2- and 4-poles is shown in Fig. 18. It is noted in Fig. 18 that $K$ in the 4-pole linear induction motor is greater than that in the 2-pole linear induction motor over a wide range of levels and that a more uniform circulating flow velocity along the outline of the molten steel pool is generated in the 4-pole linear induction motor than in the 2-pole linear induction motor. Index $K_L$, which indicates uniformity of the Lorenz force along the outline of the molten steel pool, is used to clarify the mechanism. The definition is as follows:

\[ K_L = \frac{\int_{\text{the outline of the molten steel pool}} F_L(x) \, dx}{\max(F_L(x)) \int_{\text{the outline of the molten steel pool}} dx} \quad \ldots \ldots (4) \]

where $F_L$ means the Lorenz force. $K_L$ is nearing 1 that indicates that the Lorenz force along the outline of the molten steel pool becomes more uniform, while $K_L$ becoming 0 indicates that the uniformity is lost. A comparison of the $K_L$ distributions in the 2- and 4-pole linear induction motors is shown in Fig. 19. It was found from Fig. 19 that the Lorenz force along the outline of the molten steel pool is more uniform in the 4-pole linear induction motor than in the 2-pole linear induction motor. Therefore it is obvious that the velocity along the outline of the molten steel pool, being more uniform in the 4-pole linear induction motor than in the 2-pole linear induction motor depends upon the Lorenz force distributions.

It was found from these results that a difference between the uniformity of the circulating velocity around the outline
of the molten steel pool in the 2-pole linear induction motor and that in the 4-pole linear motor occurred, though a circulating flow was generated in both cases. Considering that this phenomenon depends upon the difference between the Lorenz force distributions for the pole numbers, it can be said that the other linear induction motor variables for example, slot number, electric current frequency, which have a great effect on the Lorenz force distributions, may also have a great effect on the uniformity of the circulating velocity.

5. Summary

A numerical flow analysis was performed to clarify the basic characteristics of a circulating flow generated by the linear induction motor. The influence of the installed level
of the motor and the pole number of the linear induction motor on the circulating flow were examined.

The results of the numerical analysis were as follow:

1. The levels of the circulating flows generated and the circulating flow velocities of molten steel strongly depend on the installed levels of the linear induction motor, and

2. the uniformity of the circulating flow velocity in molten steel pool depends on the pole number, which indicate that the installed level of the motor and the pole number have a significant influence on the circulating flow. Especially the fact that the pole number has an influence on the circulating flow suggests possibility that the other linear induction motor variables, for example, slot number and frequency, also influence the circulating flow.

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