Effect of Static Magnetic Field Application on the Mass Transfer in Sequence Slab Continuous Casting Process

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A mathematical model has been developed to analyze the mass transfer in the sequence continuous casting process with the static magnetic field. The induced electromagnetic force is obtained by solving simultaneous equations for the momentum and the electromagnetic field. The application of static magnetic field affects the mass transfer by changing the flow field in the strand. The results of numerical calculation show a reasonable agreement of the calculated relative concentration of mixed steel with the measured one. The mixing of molten steel in the low part of the mold is significantly suppressed by the static magnetic field, and composition of new grade steel along the slab length in the transition zone increases significantly. The distribution of relative concentration averaged at cross section changes from parabolic to integral symbolic-like along the slab length, and the transition length is reduced about 50% by applying the magnetic field of 0.5 T.

KEY WORDS: continuous casting; mass transfer; static magnetic field application; numerical calculation.

1. Introduction

In order to improve the efficiency and flexibility of the continuous casting process, the casting of different grades of steel in a single casting sequence is widely in use at steel plants. Increasing the production efficiency of the continuous casting process requires continuous casting operation without stopping and restarting the caster. Therefore, the mixing of different grades of molten steel becomes a problem of continuous casting.

Several different processes are operated to handle the casting of different grades. Some of them are to continue casting the different grades as a single sequence and to insert the “grade-separator” etc. Each method produces different amounts of intermixed steel and incurs different costs. A common method is “flying tundish change”, which avoids stopping the caster with preventing mixing in the tundish. The tundish is changed at the same time the ladle when containing the new grade steel is opened, therefore, mixing of steel occurs only in the strand.

Huang et al. developed an intermixing model to predict quantitatively the extent of mixing in both the strand and slab as a function of casting conditions. The application of static magnetic field is used to reduce length of intermixed part in the slab in the sequence continuous casting process. Harada et al. reported the sequential continuous casting experiment by using 8 tons pilot caster with the static magnetic field. The mixing length decreased from 1.7 to 0.8 m during the change of steel grade at casting speed of 0.7 m/min when the magnetic field of the 0.5 T was applied.

The purpose of the present work is to develop a mathematical model of mass transfer of molten steel in the slab with static magnetic field and to understand the mixing mechanism of molten steel during the change of grade in a sequence continuous casting process.

2. Mathematical Formulation

Figure 1 shows the schematic of physical model for molten steel flow system with the magnets in the continuous casting mold. The flow field of molten steel contained within the solidifying shell of slab continuous casting strand is assumed to be steady and turbulent. When the strand leaves the mold, the thickness of solidifying shell is about up to 10 mm, and its effect on molten steel flow near nozzle in the mold region is small. To simplify the calculation, zero thickness of solidifying shell is assumed. Model calculation was conducted for region of one quarter of the physical strand because of the symmetry. The effect of any gradual curvature of the strand is ignored. The governing equations with the magnetic field are expressed as following formulations.

2.1. Flow Equation for Molten Steel

The molten steel flow is governed by the equations of mass conservation, momentum conservation, and turbulence motion. The equations in Cartesian coordinate system are written in three-dimensional form as Eq. (1).
The equations for each variable are shown in Table 1.

The electromagnetic force, \( F = F_x i + F_y j + F_z k \), in momentum equation is calculated by the Lorentz law:

\[
\frac{\partial (\rho \phi)}{\partial t} + \frac{\partial (\rho v \phi)}{\partial x} + \frac{\partial (\rho w \phi)}{\partial z} = \frac{\partial}{\partial x} \left( I \frac{\partial \phi}{\partial x} \right) + \frac{\partial}{\partial y} \left( I \frac{\partial \phi}{\partial y} \right) + \frac{\partial}{\partial z} \left( I \frac{\partial \phi}{\partial z} \right) + S_\phi \quad \text{(1)}
\]

The induced current density \( \vec{J} \) obeys the Ohm law as Eq. (3).

\[
\vec{J} = \sigma (\vec{E} + \vec{V} \times \vec{B}) \quad \text{(3)}
\]

\[
\vec{E} = -\nabla \phi \quad \text{(4)}
\]

The continuity of the induced current density is expressed by Eq. (5).

\[
\nabla \cdot \vec{J} = 0 \quad \text{(5)}
\]

Therefore, Eq. (6) is obtained from Eqs. (3), (4) and (5).

\[
\nabla \cdot \sigma \nabla \phi = \nabla \cdot \sigma (\vec{V} \times \vec{B}) \quad \text{(6)}
\]

An imposed magnetic field, 0.5 T, used in the calculation, was determined by the experiment as shown in Fig. 2.

\[
\frac{\partial (\rho \phi)}{\partial t} + \frac{\partial (\rho v \phi)}{\partial x} + \frac{\partial (\rho w \phi)}{\partial z} = \frac{\partial}{\partial x} \left( I \frac{\partial \phi}{\partial x} \right) + \frac{\partial}{\partial y} \left( I \frac{\partial \phi}{\partial y} \right) + \frac{\partial}{\partial z} \left( I \frac{\partial \phi}{\partial z} \right) + S_\phi \quad \text{(1)}
\]

Table 1. Variables in the common equation.

<table>
<thead>
<tr>
<th>( \phi )</th>
<th>( \Gamma )</th>
<th>( S_\phi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuity</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>x-direction momentum</td>
<td>( \mu_x )</td>
<td>( S_x = \frac{\partial (\mu_x u)}{\partial x} + \frac{\partial (\mu_x v)}{\partial y} + \frac{\partial (\mu_x w)}{\partial z} + F_x )</td>
</tr>
<tr>
<td>y-direction momentum</td>
<td>( \mu_y )</td>
<td>( S_y = \frac{\partial (\mu_y u)}{\partial x} + \frac{\partial (\mu_y v)}{\partial y} + \frac{\partial (\mu_y w)}{\partial z} + F_y )</td>
</tr>
<tr>
<td>z-direction momentum</td>
<td>( \mu_z )</td>
<td>( S_z = \frac{\partial (\mu_z u)}{\partial x} + \frac{\partial (\mu_z v)}{\partial y} + \frac{\partial (\mu_z w)}{\partial z} + F_z )</td>
</tr>
<tr>
<td>Turbulent kinetic Energy</td>
<td>( k )</td>
<td>( \frac{k}{\alpha_k} S_k = G - \rho e )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( G = \mu_k \left( \frac{\partial u}{\partial x} \right)^2 + \frac{2}{3} \left( \frac{\partial u}{\partial y} \right)^2 + \frac{2}{3} \left( \frac{\partial u}{\partial z} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2 + \left( \frac{\partial v}{\partial x} \right)^2 + \left( \frac{\partial w}{\partial z} \right)^2 + \left( \frac{\partial w}{\partial x} \right)^2 + \left( \frac{\partial w}{\partial y} \right)^2 )</td>
</tr>
<tr>
<td>Dissipation rate of turbulent kinetic energy</td>
<td>( \varepsilon )</td>
<td>( \frac{\varepsilon}{\alpha_\varepsilon} S_\varepsilon = C_1 \frac{\varepsilon}{k} - C_2 \frac{\varepsilon}{k} )</td>
</tr>
<tr>
<td>Effective viscosity ( (1) )</td>
<td>( \mu_\varepsilon = \frac{C_\varepsilon \mu_k}{\varepsilon} )</td>
<td>( \mu = \mu_0 + \mu_\varepsilon )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( C_1 = 1.44, \quad C_2 = 1.92, \quad C_\varepsilon = 0.09, \quad \alpha_k = 1.0, \quad \alpha_\varepsilon = 1.3 )</td>
</tr>
</tbody>
</table>
2.2. Mass Transfer

The mass transfer depends on convection and diffusion of molten steel in the strand. The magnetic field has effect directly on the convection and diffusion of flow field in a continuous casting process. The mixing of molten steel is calculated in the region from 0 to 2 m along z axis as shown in Fig. 1 by solving the 3-D transient diffusion equation, Eq. (7).

\[
\frac{\partial (PC)}{\partial t} + u \frac{\partial (PC)}{\partial x} + v \frac{\partial (PC)}{\partial y} + w \frac{\partial (PC)}{\partial z} = \frac{\partial}{\partial x}\left(D_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_z \frac{\partial C}{\partial z}\right) \cdots (7)
\]

Where \( C \) is the dimensionless composition, or “relative concentration,” defined by

\[
C = \frac{F(x, y, z, t) - F_{old}}{F_{new} - F_{old}} \cdots \cdots \cdots \cdots \cdots (8)
\]

\( F(x, y, z, t) \) is the fraction of a given element at a specified position in the strand or slab; \( F_{old} \) and \( F_{new} \) are the fractions of that element in old and new grade of steels, respectively.

As the flow is highly turbulent in the mold, the diffusion is accelerated significantly by turbulent eddy motion. The effective diffusivity consists of both molecular and turbulent components as shown in Eq. (9)

\[
D_z = \frac{\mu_L}{Pr} + \frac{\mu_s}{\sigma_c} \cdots \cdots \cdots \cdots \cdots (9)
\]

\( Pr \) is the Prandtl number, \( \sigma_c \) is the turbulent Schmidt number, which is assumed to be unity in the present work.

2.3. Initial Conditions

The initial conditions of velocity are obtained from the steady-state solution for the normal casting speed. The composition changes between two different grades of steel can be calculated by the relative concentration changes of two elements, A and B. “Element A” means the old grade of molten steel, “element B” means the new one. A constant initial condition at nozzle inlet is imposed on relative concentration:

\[
t \leq 0: \quad C = \begin{cases} 
1 & \text{for element A} \\
0 & \text{for element B}
\end{cases} \cdots \cdots \cdots \cdots \cdots (10)
\]

\[
t > 0: \quad C = \begin{cases} 
0 & \text{for element A} \\
1 & \text{for element B}
\end{cases} \cdots \cdots \cdots \cdots \cdots (10)
\]

2.4. Boundary Conditions

2.4.1. Flow of Molten Steel

Velocity at nozzle inlet \( V_n \) is calculated by casting speed \( V_c \) as the mass balance of molten steel flow. The turbulent kinetic energy and the rate of turbulent energy dissipation at the inlet are estimated by using the semi-empirical relation, \( k = 0.04V_n^2 \) and \( \varepsilon = 2k^{1/3}d_{nozzle} \), where \( d_{nozzle} \) is the nozzle diameter. At the free surface, the normal gradient of all the variables is the zero in addition to velocity perpendicular...
locity and turbulence fields for this problem can be obtained.

3. Results of Model Calculation

In this calculation, the effect of density difference on the mixing behavior is not considered. Therefore, the flow field is firstly solved and then the mass transfer in the sequence slab continuous casting process is analyzed. The conditions for calculation are shown in the Table 2.

Table 2. Geometrical parameters, physical properties of steel and casting conditions.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mold size, mm</td>
<td>800 (width)×170 (thickness)×2000 (length)</td>
</tr>
<tr>
<td>Nozzle size, mm</td>
<td>60 (thicknless)×60 (width)</td>
</tr>
<tr>
<td>Depth of nozzle, mm</td>
<td>150</td>
</tr>
<tr>
<td>Casting speed, m/min</td>
<td>0.7</td>
</tr>
<tr>
<td>Density of molten steel, kg/m³</td>
<td>7020</td>
</tr>
<tr>
<td>Viscosity of molten steel, m²/s</td>
<td>5.59×10³</td>
</tr>
<tr>
<td>Casting temperature, °C</td>
<td>1550</td>
</tr>
<tr>
<td>Electric conductivity of molten steel, Ω⁻¹ m⁻¹</td>
<td>7.14×10⁵</td>
</tr>
</tbody>
</table>

Figure 3 shows the typical flow velocity patterns at the upper 1.2 m portion of the strand without and with the static magnetic field. Typically, the jet impinging on the narrow face splits to flow upwards towards the top free surface and downwards toward the interior of the strand as shown in Fig. 3(a). This flow pattern changes significantly by the ap-

Fig. 3. Effect of static magnetic field on flow field at half thickness, half width and top surface, (a) without and (b) with the static magnetic field ($B_{max}=0.5$ T).

Fig. 4. The vertical velocity profile below magnetic field ($z=0.6$ m), (a) without magnetic field, (b) with the magnetic field ($B_{max}=0.5$ T).

Fig. 5. Effect of static magnetic field on the turbulent kinetic energy, (a) without and (b) with the static magnetic field ($B_{max}=0.5$ T).
plication of static magnetic field as shown in Fig. 3(b). The circulation flow below jet is significantly suppressed and plug-like flow occurs. Figure 4 shows the vertical velocity profile just below the magnet \(z=0.6 \text{ m}\). The static magnetic field application changes the velocity profile from sinusoidal wave-like to plug-like pattern. Figure 5 shows the difference of turbulent kinetic energy in the strand between without and with the magnetic field application. The significant decrease of the turbulent kinetic energy below the magnet with the application of static magnetic field was observed comparing with no static magnetic application as shown in Figs. 5(a) and 5(b).

Figure 6 shows the change of relative concentration of new grade steel with time in the strand without the magnetic field application. The concentration field corresponds to the flow pattern. The composition of new grade steel enters firstly into upper and lower circulation zones, and mixing occurs rapidly in the large zone of strand. The calculated concentrations at surface and centerline of the half width of slab are shown in Fig. 7. Comparing with the observed values, a reasonable agreement was obtained at the centerline of slab and surface. Neglecting the solidifying shell in the calculation may produce this difference. The effects of static magnetic field on the relative concentration at half thickness section are shown in Fig. 8. It is observed that the mixing occurs firstly in upper small zone, and iso-concentration line moves uniformly toward the casting direction. As the plug-like flow occurs below the magnetic field in the strand, the mixing is significantly suppressed by the static magnetic field application. Therefore, the concentration gradient of new steel composition in the transition zone along the slab is very large. Figure 9 shows a comparison of relative concentration at surface and centerline of the half width of slab between calculated and experimental values. It is noted that the calculated concentration gradient is somewhat larger than the measured one along the slab. A possible reason is the effect of assumption of zero thickness of solidifying shell on the flow pattern in the strand.

In order to understand the general trend, the relative concentration averaged at cross section is calculated by the following equation,

\[
C = \frac{\int \int_C C \, dx \, dy}{\int \int_A A \, dx \, dy}
\]  

\(\text{where} \ A \ \text{is a quarter of the cross section of slab.}\)

Figure 10 illustrates a comparison of relative concentration averaged at cross section with time between without and with the static magnetic field application. The composition of new grade steel in the transition zone along the slab changes from parabolic to integral symbolic-like, and the transition length by applying the static magnetic field of 0.5 T is reduced about 50%.

The effect of magnetic flux density on relative concentration averaged at cross section with time is shown in Fig. 11.
The distributions of the concentration are same when the magnetic flux density is more than 0.3 T. This means that the minimum magnetic flux density is 0.3 T for plug flow in the present calculation.
Figure 12 shows the effects of casting speed and magnetic field on the relative concentration averaged at cross section. The increase in the casting speed slightly increases the transition slab length. The influence of casting speed on mixing in the slab and the strand can be explained from the convection terms in the model equations described in Sec. 2.2 and casting speed has little qualitative effect on the flow pattern in the strand. It becomes clear from Fig. 12 that the effect of casting speed on the mixing length in the slab becomes small with the application of static magnetic field.

4. Conclusions

Numerical simulations of the three dimensional magneto-hydrodynamic flow and mass transfer in the sequence continuous casting process had been carried out. The following results are obtained:

1. The application of static magnetic field significantly changes the flow field in the strand. The circulation flow below jet is significantly suppressed and plug-like flow occurs. Accordingly, the significant decrease of the turbulent kinetic energy below the magnet can be obtained.

2. A reasonable agreement between calculated relative concentration and measured one reported in literature was observed at centerline of slab and surface.

3. The static magnetic field application affects the mixing process of two different steels by changing the flow field in the strand. As the plug-like flow occurs below the magnetic field, the mixing of molten steel is significantly suppressed. The distribution of relative concentration averaged at cross section changes from parabolic to integral symbolic-like along the slab, and the transition length was reduced about 50% by applying the static magnetic field of 0.5 T.

4. When the magnetic flux density is larger than 0.3 T, the relative concentration averaged at cross section has little variation with increasing magnetic flux density.

REFERENCES