Numerical Study on the Capture of Large Inclusion in Slab Continuous Casting with the Effect of In-mold Electromagnetic Stirring

Yanbin YIN,1) Jiongming ZHANG,1)* Shaowu LEI2) and Qipeng DONG1)

1) State Key Laboratory of Advanced Metallurgy, University of Science and Technology Beijing, No. 30, Xueyuan Road, Haidian District, Beijing, 100083 China. 2) Huatian Engineering & Technology Corporation, MCC, No. 18, Fuchunjiang East Street, Jianye District, Nanjing, 210019 China.

(Received on June 20, 2017; accepted on August 17, 2017; J-STAGE Advance published date: October 13, 2017)

Large inclusions captured by the solidifying shell deteriorate the surface quality of interstitial free steel. To investigate the capture of large inclusion in slab continuous casting, a three-dimensional model coupling flow field, solidification and inclusion motion has been developed. Additionally, to study the effect of in-mold electromagnetic stirring (M-EMS) on large inclusion capture, the electromagnetic field has been also coupled in the model. The results of electromagnetic field indicates its centrally symmetrical distribution on the cross-section, and the electromagnetic force swirls on the cross-section. The effects of M-EMS on flow pattern, solidification and inclusion capture have been discussed. The M-EMS significantly changes the flow pattern and solidifying shell thickness. The inhomogeneous distribution of large inclusions existing in the slab surface in the slab surface are different between the cases with and without M-EMS. Furthermore, the number of captured inclusions increases at 0–0.02 m beneath the wide surface and decreases at 0.02–0.04 m beneath the wide surface in response to the application of M-EMS. Large inclusions in steel were quantitatively analyzed by the galvanostatic electrolysis method. The experimental results are in agreement with the simulation results, suggesting that the model is valid.

KEY WORDS: numerical simulation; M-EMS; solidification; inclusion capture; flow; slab continuous casting.

1. Introduction

Interstitial free (IF) steel is widely used in the automobile industry for its excellent deep-drawing property. But surface defects such as slivers and pencil blisters in the final product always result in rejections and downgrading.1) Large inclusions (>50 μm) captured by the solidifying shell are the primary source of those defects. In recent decades, in-mold electromagnetic stirring (M-EMS) has been applied extensively in continuous casting.2) It is generally recognized that M-EMS can improve surface qualities of continuous casting steels.3–5) Stirring the molten steel in the specific region of the mold is generally used to change the flow pattern. Besides, the flow pattern affects the inclusion capture and the molten steel’s solidification in the mold. Hence, an in-depth analysis of the effect of M-EMS on inclusion capture and distribution is of great importance, and it can provide theoretical guidance for IF steel production.

In recent years, great efforts have been devoted to research on the particle (inclusion, bubble) behaviors in continuous casting through numerical simulation.6–24) Many previous works13–20) have studied the capture of inclusions or bubbles by the solidifying shell in continuous casting. Yuan Q. et al.13) used a Lagrangian trajectory tracking method, coupling time-dependent flow fields obtained from large-eddy simulation (LES), to predict particle motion and capture in a thin-slab steel caster. Particles studied in the work were smaller than the primary dendrite arm spacing (PDAS), which could lead to particles entrapment easily. The locations of captured particles and distribution of total oxygen in the final steel slab were predicted, based on the computations. Zhang L. et al.14) established two 3-D numerical models to study the entrapment of inclusions in continuous-casting billets. One ignored the heat transfer and solidification, using the sink term approach to represent the mass and momentum loss during the solidification. The other one considered the effect of turbulent flow, heat transfer, solidification. Comparisons with the experimental measurement and simulation results were performed, and the calculated inclusion distribution by the full solidification approach agreed well with the industrial measurement. Thomas B. G. et al.15) simulated the entrapment of slag inclusions and bubbles during the continuous casting of steel slabs. A particle capture criterion based on local force balances and PDAS was applied. The results suggested that particle size and density, transverse fluid, PDAS, solidification front orientation angle, and sulfur concentration gradient affected the particle capture jointly. Liu Z. et al.16) investigated the transport and entrapment of particles in a continuous casting mold, using a coupled mathematical model. The LES approach was used to calculate turbulence of molten steel inside the liquid pool. The results indicated that the transient flow pattern and particle distributions were asymmetric. Furthermore, particle capture positions were presented in the work.

A few previous studies11,12,23–30) have investigated the effect of the electromagnetic field application on the particle behaviors in continuous casting. Researchers mainly paid attention to particle removal during continuous casting.11,12,23–30) Few works studied the effect of the electro-
magnetic field application on the particle capture during continuous casting. Liu Z. et al. studied the effects of electromagnetic brake (EMBr) arrangement and magnetic field strength on inclusion transport and entrapment in a slab mold, using a mathematical model coupling flow field, magnetic field and inclusion transport. In this model, the flow field was calculated by the LES approach, however, heat transfer and solidification were not considered. Wang et al. established a three-dimensional model coupling fluid flow, heat transfer, magnetic field and solidification in a FC (flow control)-Mold, to investigate the effect of electromagnetic parameters on the motion and entrapment of inclusions. At present, studies about the capture of particles in the slab mold with the effect of M-EMS have not been reported.

The current work presents a three-dimensional model coupling the electromagnetic field, fluid flow, solidification, and inclusion motion in slab continuous casting, using the CFD package OpenFOAM 2.1.1. The electromagnetic field has been calculated by ANSYS 12.0, and then the calculated electromagnetic force is incorporated into the Navier–Stokes equation. This present work has provided the distributions of the electromagnetic field and flow field in the mold with EMS. The effects of M-EMS on the flow pattern, solidification and large inclusion capture have been discussed. To validate the model, the present work has extracted large inclusions in steel by the method of galvanostatic electrolysis.

2. Numerical Model

The numerical model mainly involves three parts: the solidification and flow model, the inclusion capture model and the M-EMS model. The solidification and flow model used for solving the initial conditions (temperature field, flow field and the solidification shell distribution) of the inclusion capture behavior is steady. Further, a transient model coupled the solidification, fluid flow, and inclusion capture is solved to simulate the inclusion motion and capture in the domain with a Lagrangian approach. The M-EMS model is a finite element method, which could capture in the domain with a Lagrangian approach. The solidification and flow model, the inclusion capture model and the M-EMS model. The solidification and flow model, the inclusion capture model and the M-EMS model. The solidification and flow model, the inclusion capture model and the M-EMS model. The solidification and flow model, the inclusion capture model and the M-EMS model. The solidification and flow model, the inclusion capture model and the M-EMS model. The solidification and flow model, the inclusion capture model and the M-EMS model. The solidification and flow model, the inclusion capture model and the M-EMS model. The solidification and flow model, the inclusion capture model and the M-EMS model. The solidification and flow model, the inclusion capture model and the M-EMS model. The solidification and flow model, the inclusion capture model and the M-EMS model. The solidification and flow model, the inclusion capture model and the M-EMS model. The solidification and flow model, the inclusion capture model and the M-EMS model. The solidification and flow model, the inclusion capture model and the M-EMS model. The solidification and flow model, the inclusion capture model and the M-EMS model. The solidification and flow model, the inclusion capture model and the M-EMS model. The solidification and flow model, the inclusion capture model and the M-EMS model. The solidification and flow model, the inclusion capture model and the M-EMS model. The solidification and flow model, the inclusion capture model and the M-EMS model. The solidification and flow model, the inclusion capture model and the M-EMS model.

2.2. The M-EMS Model

The magnetic flux density and the induced current density are solved through the Maxwell equations, which are defined as follows:

\[ \nabla \times \vec{B} = \frac{\partial \vec{E}}{\partial t}, \] (2)

\[ \nabla \times \vec{H}_{EM} = \vec{J}, \] (3)

\[ \vec{J} = \sigma \vec{E}, \] (4)

\[ \vec{H}_{EM} = \frac{\vec{B}}{\mu_{EM}}, \] (5)

where \( \vec{E} \) is electric field intensity, \( \vec{B} \) is magnetic flux density, \( \vec{H}_{EM} \) is magnetic field intensity, \( \vec{J} \) is current density, \( \mu_{EM} \) is magnetic permeability, and \( \sigma \) is electrical conductivity. Assuming that the electromagnetic field is harmonic, the electromagnetic force can be decomposed into time-dependent and time-independent components. Because the electromagnetic field period is much shorter than the momentum response time of the molten steel, the time averaged value could be used to couple with other variables. The time averaged electromagnetic force is defined as follows:

\[ \vec{F}_{mag} = \frac{1}{2} Re(\vec{J} \times \vec{B}'), \] (6)

where \( \vec{B}' \) is conjugate complex number of \( \vec{B} \), and \( Re \) is the real part of a complex quantity.

2.2. The M-EMS Model

2.3. The Flow and Solidification Model

2.3.1. Basic Conservation Equations

The mass and momentum conservation equations take the follow forms:

\[ \nabla \cdot (\rho \vec{u}) = 0, \] (7)

\[ \frac{\partial}{\partial t} (\rho \vec{u}) + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \cdot (\mu_{eff} \nabla \vec{u}) + S_v + \vec{F}_{mag}, \] (8)

where \( \rho \) is molten steel density, \( \vec{u} \) is molten steel velocity, \( \mu_{eff} \) is effective viscosity of the molten steel, \( p \) is pressure, \( S_v \) is momentum source term which will be described in the next section, \( \vec{F}_{mag} \) is electromagnetic force. \( \mu_{eff} \) is derived from the formula as follows:

\[ \mu_{eff} = \mu + c_\mu \frac{\rho k^2}{\varepsilon}, \] (9)

The term \( \mu \) on the right side of Eq. (19) represents the molecular viscosity of molten steel, which is a physical parameter. \( c_\mu \) is a constant, whose value is 0.09 according to the work of Launder B. E. and Spalding D. B. \( k \) and \( \varepsilon \) are turbulent kinetic energy and turbulent energy dissipation rate respectively, which are calculated by the standard \( k-\varepsilon \) turbulence model written in tensor form as follows:

\[ \frac{\partial}{\partial t} (\rho k) + \rho (\nabla \vec{u} \cdot \nabla) = \nabla \cdot \left[ \left( \mu + \frac{\mu_{\text{eff}}}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + G_k - \rho \varepsilon, \] (10)

\[ \frac{\partial}{\partial t} (\rho \varepsilon) + \rho (\nabla \vec{u} \cdot \nabla) \varepsilon = \nabla \cdot \left( \left( \mu + \frac{\mu_{\text{eff}}}{\sigma_\varepsilon} \right) \nabla \varepsilon \right) + C_\mu \frac{\varepsilon}{k} G_k - C_\varepsilon \rho \frac{\varepsilon^2}{k}, \] (11)

where \( G_k \) represents the production of turbulence kinetic energy due to the mean velocity gradients:

\[ G_k = -\rho \vec{u} \cdot \frac{\partial \vec{u}}{\partial x}, \] (12)

and \( C_1, C_2, \sigma_1, \sigma_2 \) are constants given by B. E. Launder and D. B. Spalding as follows:

\[ C_1 = 1.44, C_2 = 1.92, \sigma_1 = 1.0, \sigma_2 = 1.3, \] (13)
2.3.2. Enthalpy-Porosity Technique

The present work has adopted enthalpy-porosity technique\(^\text{33}\) to simulate heat transfer and solidification, which treats the mushy region as a "pseudo" porous medium. A variable called the liquid fraction, which indicates the volume fraction of steel in liquid form, is computed for each cell in the simulation domain at each iteration. The liquid fraction, \(f\), can be described as:

\[
f = \begin{cases} 
0 & \text{if } T < T_{\text{solidus}} \\
\frac{T - T_{\text{solidus}}}{T_{\text{liquidus}} - T_{\text{solidus}}} & \text{if } T_{\text{solidus}} \leq T \leq T_{\text{liquidus}} \\
1 & \text{if } T > T_{\text{liquidus}}
\end{cases}
\]  

where \(T_{\text{solidus}}\) and \(T_{\text{liquidus}}\) are solidus and liquidus temperature respectively.

The enthalpy of the steel, \(H\), is computed as the sum of the sensible enthalpy, \(h\), and the latent heat, \(\Delta H\):

\[
H = h + \Delta H
\]

where \(h = h_{\text{ref}} + \int_{T_{\text{ref}}}^{T} c_{p} dT\).

The latent heat content can be written in terms of the steel latent heat \(L\):

\[
\Delta H = f L
\]

where \(h_{\text{ref}}\) is reference enthalpy, \(T_{\text{ref}}\) is reference temperature, \(c_{p}\) is steel specific heat at constant pressure. The energy conservation equation can be written as:

\[
\frac{\partial}{\partial t}(\rho H) + \nabla \cdot (\rho \mathbf{u} H) = \nabla \cdot \left( k_{\text{eff}} \nabla T \right),
\]

where \(k_{\text{eff}}\) is effective thermal conductivity, \(k\) is thermal conductivity, \(k_{t}\) is turbulent thermal conductivity, \(Pr_{t}\) is turbulent Prandtl number which is 0.85 by default.

In mushy zone, the porosity is equal to the liquid fraction. When the molten steel has fully solidified, the liquid fraction and porosity become zero, and the velocity of solidified steel is equal to the casting speed. The influence of porosity on fluid flow velocities is dramatic, which can be introduced into the momentum conservation equation source term:

\[
S_{i} = \frac{(1 - f)}{f} A_{\text{mush}} \left( \mathbf{u} - \mathbf{u}_{\text{cast}} \right)
\]

where \(e\) is a small number (0.001) to prevent division by zero, \(A_{\text{mush}}\) is mushy zone constant, and \(\mathbf{u}_{\text{cast}}\) is casting velocity.

2.4. Particle Force Balance Equation

The movement of the inclusions is governed by the particle force balance equation defined as follows:

\[
\rho_{p} \frac{d\mathbf{u}_{p}}{dt} = \mathbf{F}_{\text{drag}} + \mathbf{F}_{b} + \mathbf{F}_{v} + \mathbf{F}_{VM} + \mathbf{F}_{0},
\]

where \(\rho_{p}\) is inclusion density, \(d_{p}\) is particle diameter, \(\mathbf{u}_{p}\) is particle velocity, \(\mathbf{F}_{\text{drag}}\) is particle drag force, \(\mathbf{F}_{b}\) is pressure gradient force, \(\mathbf{F}_{v}\) is buoyancy force, \(\mathbf{F}_{VM}\) is virtual mass force, \(\mathbf{F}_{0}\) is Saffman force.

Drag force\(^\text{33}\) can be described as:

\[
\mathbf{F}_{\text{drag}} = \frac{8}{2} d_{p} C_{D} \rho_{s} \left( \mathbf{u}_{p} - \mathbf{u} \right) \left( \mathbf{u}_{p} - \mathbf{u} \right),
\]

where \(C_{D}\) is a dimensionless drag coefficient as a function of particle Reynolds number, according to the approach of C. T. Crowe et al.\(^{33}\) \(C_{D} = 1 + 0.15 Re_{p}^{0.687} \times \frac{241}{Re_{p}}\), \(Re_{p} = \rho d_{p} \left( \mathbf{u}_{p} - \mathbf{u} \right) / \mu\), \(Re_{p}\) is particle Reynolds number. \(\mathbf{u}_{p}\) is molten steel instantaneous velocity, which will be described below.

The pressure gradient force\(^{33}\) can be given as follows:

\[
\mathbf{F}_{p} = -\frac{\pi}{6} d_{p} \nu \mathbf{p}.
\]

The buoyancy force can be expressed as:

\[
\mathbf{F}_{b} = \frac{\pi}{6} d_{p} \left( \rho_{s} - \rho_{p} \right) \mathbf{g},
\]

where \(\mathbf{g}\) is the gravitational acceleration.

The virtual mass force,\(^{33}\) takes in account that an accelerating or decelerating body should accelerate a volume of surrounding fluid equal to one half of the volume a sphere displaces:

\[
\mathbf{F}_{VM} = \frac{\pi}{6} d_{p} \rho_{s} \mathbf{C}_{VM} \frac{d}{dt} \left( \mathbf{u}_{p} - \mathbf{u} \right).
\]

The stochastic transport of particles (STP)\(^3\) is adopted to incorporate the stochastic effect of turbulent fluctuations on particle. In STP model, velocity fluctuations are based on a Gaussian-distributed random number chosen according to the kinetic energy of the local turbulence. The random number is changed to produce a new instantaneous velocity fluctuation at a frequency equal to the characteristic lifetime of the eddy. The instantaneous molten steel velocity is then given by:

\[
\mathbf{u}_{i} = \mathbf{u}_{i} + \mathbf{u}_{i} = \mathbf{u}_{i} = \frac{1}{2} \xi (2k / 3)^{1/2},
\]

where \(\mathbf{u}_{i}\) is mean velocity component of the molten steel in direction \(i\), \(\mathbf{u}_{i} \) is component of Gaussian-distributed random velocity fluctuation in direction \(i\), and \(\xi\) is a random number.

2.5. Geometry Model and Boundary Conditions

2.5.1. Geometry Model

Figure 1(a) shows the M-EMS geometry model. Travelling-wave electromagnetic stirrer with 30 pairs of coils around the straight iron cores has been designed to stir the molten steel in the mold. All the coils are connected to a low frequency three-phase AC current (3 Hz, 400 A). The copper plate of the mold is 30 mm in thickness. As Fig. 1(b) shows, a full geometry model has been developed for the coupling simulation, a slab (0.8 m in mold, 1.2 m in second cooling zone) with a size of 1.6 m × 0.25 m × 2 m is divided into cells of which the minimum and maximum sizes are 0.001 m and 0.01 m, respectively. The submerged depth of the nozzle is 0.2 m, and the nozzle inner diameter is 0.085 m. The SEN port is rectangular, with a height of 0.075 m, a width of 0.07 m and pointing 15 degrees downward.

To simulate the behavior of the initial solidifying shell more accurately, local grid refinement technology is applied. To facilitate the discussion, slab wide face whose \(Y\)-value is negative is called lower wide face, by contrast, slab wide face whose \(Y\)-value is positive is called upper wide face. For example, the \(Y=0.125\) m and −0.125 m planes are called upper and lower wide surface respectively.
2.5.2. Boundary Conditions

(1) Boundary Conditions for Electromagnetic Simulation

An air cuboid (2.83 m × 1.16 m × 2.45 m) around the whole geometry model is used to capture a great part of the magnetic field lines closing in the surrounding air. Boundary conditions are applied on the external surfaces of the surrounding air cuboid with magnetically flux parallel boundary. Moreover the electromagnetic field is equal to zero on the external surfaces of the surrounding air cuboid. On the other surfaces, Neumann magnetically flux vertical boundary conditions are adopted.\footnote{36}

(2) Boundary Conditions for Flow and Solidification Simulation

For nozzle inlet boundary conditions, all variables are assumed to be constant. The inlet velocities of molten steel and inclusions are assumed to be identical, which are defined using the casting speed. Additionally, the molten steel temperature at nozzle inlet, and $A$ is the thickness of casting velocity in the $z$-direction, $A$ is the thickness of steel temperature in tundish. The velocity of solidifying molten steel temperature at nozzle inlet, and $\gamma$ is the average heat transfer coefficient between the slab surface and the surroundings, $H_s$ represents the steel enthalpy at the surface and $H_e$ represents the product of ambient temperature and the specific heat of steel. $Q_{\text{water}}$ (L·m$^{-2}$·s$^{-1}$) is water flux in the second cooling zone, $T_{\text{spray}}$ is the temperature of the cooling-water spray. According to the work of Meng Y. and Thomas B. G.,\footnote{40} $A$, $c$ and $b$ are set as 0.3925, 0.55 and 0.0075 respectively.

$$Q = \left[2.64 \times \exp\left(-\left(\frac{z}{U_{cast}}\right)^{0.91}\right)\right] \times 10^6,$$

where $Q$ (J·m$^{-2}$·s$^{-1}$) is heat flux extracted from the mold wall, $z$ is distance from the meniscus.

In the secondary cooling zone, the thermal boundary condition can be described as follows:\footnote{39,40}

$$\frac{\partial H}{\partial x} = \frac{\partial H}{\partial y} = \gamma \frac{k_{eff}}{H_s} (H_s - H_e), \quad \frac{\partial H}{\partial z} = 0.$$

3. Results and Discussion

3.1. The Distribution of Electromagnetic Field

The traveling-wave M-EMS is a dynamic process. The electromagnetic field varies along the width direction of the mold; in other words, the present magnetic field originates from the single-directional movement of the previous one.
**Table 1.** The Material properties and model parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>(c_p), Specific heat</td>
<td>700</td>
<td>J(\cdot)kg(^{-1})(\cdot)K(^{-1})</td>
</tr>
<tr>
<td>(k'), Thermal Conductivity</td>
<td>31</td>
<td>W(\cdot)m(^{-1})(\cdot)K(^{-1})</td>
</tr>
<tr>
<td>(\rho), Steel density</td>
<td>7.000</td>
<td>kg(\cdot)m(^{-3})</td>
</tr>
<tr>
<td>(L), Steel latent Heat</td>
<td>264 000</td>
<td>J(\cdot)kg(^{-1})</td>
</tr>
<tr>
<td>(T_L), Liquid Temperature</td>
<td>1 807</td>
<td>K</td>
</tr>
<tr>
<td>(T_S), Solid Temperature</td>
<td>1 797</td>
<td>K</td>
</tr>
<tr>
<td>(\mu), Molecular viscosity of the molten steel</td>
<td>0.0055</td>
<td>kg(\cdot)s(^{-1})(\cdot)m(^{-1})</td>
</tr>
<tr>
<td>(U_{cast}), Casting speed</td>
<td>0.02</td>
<td>m(\cdot)s(^{-1})</td>
</tr>
<tr>
<td>(T_{tun}), Tundish temperature</td>
<td>1 827</td>
<td>K</td>
</tr>
<tr>
<td>Mold length</td>
<td>0.8</td>
<td>m</td>
</tr>
<tr>
<td>Second cooling zone length in geometry model</td>
<td>1.2</td>
<td>m</td>
</tr>
<tr>
<td>Iron core length</td>
<td>2.43</td>
<td>m</td>
</tr>
<tr>
<td>Iron core thickness</td>
<td>0.2</td>
<td>m</td>
</tr>
<tr>
<td>Iron core width</td>
<td>0.23</td>
<td>m</td>
</tr>
<tr>
<td>Iron core width</td>
<td>0.23</td>
<td>m</td>
</tr>
<tr>
<td>EMS position from the meniscus to the stirrer mid-plane</td>
<td>0.45</td>
<td>m</td>
</tr>
<tr>
<td>M-EMS coil current density</td>
<td>400</td>
<td>A</td>
</tr>
<tr>
<td>M-EMS coil current frequency</td>
<td>3</td>
<td>Hz</td>
</tr>
<tr>
<td>Liquid steel electric conductivity</td>
<td>7.14e5</td>
<td>S(\cdot)m(^{-1})</td>
</tr>
<tr>
<td>Liquid steel magnetic conductivity</td>
<td>1.257e-6</td>
<td>H(\cdot)m(^{-1})</td>
</tr>
</tbody>
</table>

**Figure 3.** Vector and contour plots of magnetic flux density (a) and time-averaged electromagnetic force (b) on the stirrer mid-plane \((Z = -0.45 \text{ m})\). (Online version in color.)

**Figure 4.** Time-averaged electromagnetic force profiles: (a) along the mold corner \((X = 0.8 \text{ m}, Y = 0.125 \text{ m})\); (b) along the wide-face centerline of the stirrer mid-plane \((Z = -0.45 \text{ m})\); (c) along \(Y = 0.0625 \text{ m}\) and \(Y = -0.0625 \text{ m}\) lines of the stirrer mid-plane \((Z = -0.45 \text{ m})\). (Online version in color.)
Moreover the directions of the electromagnetic force component in Y-axis direction tend to alternate between positive and negative. It is this trend of the electromagnetic force that gives rise to the transverse swirls of the molten steel. Figure 4(c) shows the time-averaged electromagnetic force profiles along \( Y = 0.0625 \) m and \( Y = -0.0625 \) m lines of the stirrer mid-plane. The trends of the electromagnetic force components in the Y-axis and Z-axis directions are similar to those shown in Fig. 4(b). Nevertheless, the X-axis component of the electromagnetic force presents a new feature. The X-axis components of the electromagnetic force along \( Y = 0.0625 \) m and \( Y = -0.0625 \) m lines are larger than those along the wide-face centerline, ranging from 10 000 N/m\(^3\) to 15 000 N/m\(^3\), and their direction are consistent.

### 3.2. Effect of M-EMS on Flow and Solidification

The 2-D streamlined distributions on the longitudinal sections in the case without M-EMS and with M-EMS are shown in Figs. 5 and 6, respectively. When M-EMS is off, the streamline is symmetrical about the vertical centerline.
of the longitudinal section. The jet exiting the nozzle travels across the mold cavity and, splits into upward and downward flowing jets. This diverted flow creates the classic upper and lower recirculation zones of a double-roll flow pattern. Furthermore, two small swirls exist beneath the SEN. The lower recirculation zone is much larger because it is not confined. The upper zone is constrained by the top surface and the jet exiting the SEN. By comparing the streamlines on the three longitudinal planes, it can be found that the upper recirculation zones are similar. Nevertheless, the lower recirculation zone on the wide-face center plane is larger than those on the wide-face quarter planes, because the velocity of the downward jet on the wide-face center plane is larger than those on the wide-face quarter planes. When M-EMS is applied, the molten steel flow pattern in the domain has been obviously changed. The classical double-roll flow pattern can only be observed on the wide-face center plane, because the X-axis and Z-axis components of the electromagnetic force shown in Fig. 4(b) are tiny and their effects on the molten steel velocities are negligible. Figures 6(a) and 6(c) reveal the 2-D streamlined distributions on the lower and upper quarter planes of the wide face (\(Y = -0.625\) m and \(Y = 0.625\) m planes), the arrows indicate the directions of the electromagnetic force X-axis component. On the lower quarter plane of wide face, the lower and upper recirculation zones disappear on the right side, and the molten steel flows to the left side. On the left side, the lower and upper recirculation zones are diminished. It is the X-axis component of the electromagnetic force displayed in Fig. 4(c) that enhances the flow on the left side and restrains the flow on the right side. On the upper quarter plane of wide face, the situation is just the opposite, because the X-axis component of the electromagnetic force enhances the flow on the right side and restrains the flow on the left side.

Figure 7 shows contour plot of the solidifying shell thickness on the slab wide face. The liquid fraction is 0.2 at the solidifying front. As is shown in Fig. 7(a), the solidifying shell in the case without M-EMS is symmetric about the centerline of the slab wide face. When M-EMS is off, the flow pattern that the flow field is symmetrical about the wide face centerline and there are no obvious transverse swirls leads to the distribution of solidifying shell. Nevertheless, the distribution of solidifying shell in the case with M-EMS is changed when the M-EMS is applied. As is shown in Figs. 7(b) and 7(c), the solidification shell is not symmetric about the slab wide face centerline. Two special zones (Zone A and Zone B), at which solidifying shells are thin obviously, appear at the margin of wide face. To discuss this phenomenon, contour plot of liquid fraction and 2-D streamline plot on the stirrer mid-plane (\(Z = -0.45\) m) in the cases without M-EMS and with M-EMS are demonstrated in Fig. 8.

As is shown in Fig. 8(a), when M-EMS is off, the flow of molten steel on the transverse plane is relatively homogenous, and molten steel flows mainly along the width direction. Molten steel merely presents a thickness direction flow along the vertical centerline of the transverse plane. The solidifying shell is also relatively homogenous. When M-EMS is applied, there are four transverse swirls of the molten steel, which almost coincide with those four transverse swirls of electromagnetic force shown in Fig. 3(b). Those transverse swirls of molten steel result in the inhomogeneity of heat transfer and impact on the solidifying shell. Consequently, the solidifying shell is inhomogeneous. As is shown in Fig. 3(b), the time-averaged electromagnetic forces on the upper left and lower right corners of the cross-section are outward. As a result, the molten steel flows to the solidifying shell and impacts the solidifying shell at the two positions, which results in the existences of Zone A and Zone B. It is assumed that the M-EMS has an influence on the solidification of the molten steel indirectly, through changing the flow pattern.

3.3. Effect of M-EMS on Large Inclusion Capture

Figures 9 and 10 reveal the distributions of large inclusions over 50 \(\mu\)m at 0–0.04 m under the upper wide surface in the cases without M-EMS and with M-EMS. The shadow zones in the figures represent the inclusion capture zones at the solidifying front. The experiment samples were obtained from the pattern zones filled with diagonals. In the case without M-EMS, the inclusion capture zones are symmetric about the centerline of the slab wide face; nevertheless, in the case with M-EMS, those are not symmetrical. This is due to the asymmetry of the solidifying shell caused by the electromagnetic force. The results suggest that large inclusions are mainly concentrated at 0.01–0.03 m under the upper wide surface for both cases.

In the case without M-EMS, the inclusions larger than 176 \(\mu\)m in diameter mainly exist at 0.01–0.03 m below the upper wide surface. The inclusions with a diameter of
Fig. 10. Inclusion distributions (larger than 50 μm) in the case with M-EMS at different locations under the surface of the slab wide face: (a) 0–0.01 m; (b) 0.01–0.02 m; (c) 0.02–0.03 m; (d) 0.03–0.04 m (the particles represent the captured inclusions and are colored by their diameters). (Online version in color.)

larger than 194 μm only exist at 0.03–0.04 m below the upper wide surface. In the case with M-EMS, the inclusions larger than 176 μm in diameter mainly exist at 0.01–0.02 m under the upper wide surface. No inclusions larger than 194 μm in diameter can be captured by the solidifying front. It is assumed that the M-EMS affected the flow pattern and solidifying shell thickness. Consequently, the inclusion distributions are different between the case without M-EMS and with M-EMS.

As are shown in Figs. 9 and 10, it can be found in that some clusters of captured inclusions exist in the solidifying shell, and the clustering positions are different for the two cases. Figure 11 reveals the number variations of captured inclusions along the width direction at the slab wide face for the two cases. As is indicated in Fig. 11(a), when M-EMS is off, the distributions of the inclusions at 0–0.01 m and 0.01–0.02 m below the upper wide surface are more homogeneous than those at other locations. At 0.02–0.04 m below the upper wide surface, inclusion clusters appear near the quarter of the slab wide face. As is shown in Fig. 11(b), when M-EMS is applied, the positions of the inclusion clusters have changed significantly. At 0–0.01 m under the upper wide surface, inclusion clusters appear at center of the wide face and the right 1/8 of the wide face. At 0.01–0.02 m under the upper wide surface, inclusion clusters appear at center and right edge of the wide face. At 0.02–0.03 m under the upper wide surface, inclusion clusters appear at the right and left edges of the wide face. At 0.03–0.04 m under the upper wide surface, the distribution of the inclusions is relatively even.

Figure 12 shows the size distribution and number of captured inclusions at the slab wide face. In both cases, the captured inclusions are mainly located at 0.01–0.03 m beneath the upper wide surface. At 0–0.02 m under the upper wide surface, the total numbers of the captured inclusions in the case with M-EMS are larger than those in the case without M-EMS. Furthermore, the numbers of the captured inclusions in different size groups are larger in the case with M-EMS except the number of the captured inclusions ranging in size from 150 μm to 175 μm at 0–0.01 m.
under the upper wide surface. At 0.02–0.04 m under the upper wide surface, the total numbers of the captured inclusions in the case without M-EMS are less than those in the case with M-EMS. Moreover, the numbers of the captured inclusions in different size groups are less in the case with M-EMS except the number of the captured inclusions in the 125–150 μm group at 0.02–0.03 m under the upper wide surface. At 0.01–0.02 m and 0.03–0.04 m under the upper wide surface, there are notable differences between the total captured inclusion numbers in the cases without EMS and with EMS.

Figure 13 shows the area of the inclusion capture zone at different distances under the upper wide surface. The areas at 0–0.02 m beneath the upper wide surface in the case with EMS are larger than those in the case without M-EMS, and the difference between the two cases is especially pronounced at 0.01–0.02 m beneath the upper wide surface. This may account for the variations of the total captured inclusions between the two cases at the two locations. At 0.02–0.03 m beneath the upper wide surface, the area of the inclusion capture zone in the case with M-EMS is larger than that in the case without M-EMS. However, since the total number of the captured inclusions increases when M-EMS is applied at 0–0.02 m beneath the upper wide surface, the number of inclusions which can be captured at 0.02–0.04 m beneath the upper wide surface would decrease. Therefore, the total number of captured inclusions in the case with M-EMS is less than that in the case without M-EMS. Besides, at 0.03–0.04 m beneath the upper wide surface, the area of the inclusion capture zone in the case with M-EMS is smaller than that in the case without M-EMS, so the variation of the captured inclusion number between the two cases is considerable.

4. Model Validation

In order to validate the model, the present work has quantitatively extracted large inclusions in steel adopting the method of galvanostatic electrolysis. The steel samples under the same process parameters used in the present work have been taken in a steel plant. The composition of the non-aqueous electrolyte is 99% ethanol and FeCl₃. Figure 14 shows the device used in this method. The steel sample served as the anode. For the sake of protecting the steel samples from oxidation, this method took advantage of an argon atmosphere. The size of the steel sample is 0.1 m × 0.15 m × 0.04 m. The electrolyte is filtered by a nylon membrane filter with an open pore size of 50 μm to obtain the inclusions. Subsequently, the inclusions are weighed by an analytical balance, and particle sizes were measured by microscope at a magnification of 30–45x.

The inclusion numbers and masses have been obtained from the pattern zones filled with diagonals, as shown in Figs. 9 and 10. The inclusion weights have been calculated from the equation as follows:

\[ m_p = \sum_{i=1}^{n} \frac{4}{3} \pi r_p^3 \rho_p \] 

where \( n \) is the maximum number of the inclusion within the same radius, \( \rho_p \) is the density of the inclusion, and \( r_p,i \) is the radius of the i-th inclusion. In order to normalize the datum, for every case, the present work sum the datum of the three positions, and then evaluates the proportions at each position.

Figure 15 reveals inclusion number percentages and mass percentages at different positions of the slab wide face for different cases. The results suggest that the variation trends of the number and mass percentages are similar for both the experiment and simulation, which validates the model. The inclusion number percentages and mass percentages are high at the quarter of the slab wide face for the experiment and simulation without M-EMS. However, with M-EMS, the percentages of number and mass are low at the quarter of the slab wide face.
5. Conclusions

The present work has built a three-dimensional model coupling the electromagnetic field, flow field, solidification and inclusion motion. The present work has investigated inclusion capture in the solidification process of slab continuous casting with the effect of M-EMS. The distributions of magnetic flux density and time-averaged electromagnetic force have been reported. The effects of the M-EMS on the flow field, solidification and inclusion capture in the process have been revealed. The conclusions are as follows:

(1) The distributions of magnetic flux density and time-averaged electromagnetic force are centrally symmetrical on the cross-section of the mold. Also, for the time-averaged electromagnetic force, four small transverse swirl zones exist in the interior of the mold.

(2) The M-EMS changes the flow pattern of the molten steel in the mold. When M-EMS is off, the flow field present a classic double-roll flow pattern. When M-EMS is applied, the transverse flow in the mold is enhanced, and the classical double-roll flow pattern can only be observed on the wide-face center plane.

(3) The M-EMS has an influence on the solidification of the molten steel indirectly by changing the flow pattern. The solidifying shell without EMS is symmetrical about the centerline of the wide face. Nevertheless, with M-EMS, the solidifying shell is not symmetric about the centerline of the wide face. Besides, two special zones, at which solidifying shells are obviously thin, appear at the margin of wide face.

(4) Large inclusions are mainly concentrated at 0.01–0.03 m under the wide surface for the both cases. Some clusters of captured inclusions exist in solidifying shell, and there are different cluster positions in the two cases. At 0.02–0.04 m under the upper wide surface, the situation is just the reverse.

Acknowledgments

The authors gratefully express their appreciation to the National Natural Science Foundation of China (U1360201) and (51474023) for sponsoring this work.

REFERENCES

17) S. Lei, J. Zhang, X. Zhao and K. He: ISIJ Int., 54 (2014), 94.
20) S. Lei, J. Zhang, X. Zhao and K. He: ISIJ Int., 54 (2014), 94.