Numerical Simulation of Flow, Heat, Solidification, Solute Transfer and Electromagnetic Field for Vertical Mold and Curved Mold of Billet

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A three-dimensional model, which coupled flow, heat transfer, solidification, solute transport and electromagnetic field, was separately developed for vertical mold and curved mold of billet continuous casting. Therefore, the characteristics and disciplinarians of macroscopic transport behavior for different types of mold were revealed. The influence of mold electromagnetic stirring (M-EMS) and mold curvature on the flow, heat transfer, solidification, solute transport in the mold were investigated in detail. The results indicate that the M-EMS can cause obvious rotating flow in the mold and enhance the superheat dissipation of the molten steel to promote the growth of solidification shell. The mold curvature has a profound effect on the flow field distribution of the mold, and further affects the temperature field and solute distribution in the mold. Therefore, the mold curvature is necessary to consider for predicting the macroscopic transmission phenomenon in the mold. Moreover, the predicted and experimental results for distributions of magnetic flux density and near surface element C content compare agreeably, which indicates the validity of the coupled model in current work.

KEY WORDS: coupling model; mold electromagnetic stirring; macroscopic transport behavior; mold curvature; billet.

1. Introduction

As a very important part of the continuous casting (CC) process, the CC mold has always been concerned and studied by researchers. In the CC process, the molten steel enters the mold through the submerged entry nozzle (SEN) and forms obvious flow pattern in the mold. In addition, there are other macroscopic transport behaviors such as heat transfer, solidification and solute distribution in the mold, which are closely related to the formation of most defects in the billet. Therefore, it is necessary to investigate the macroscopic transport behaviors in the mold.

It is well known that the CC process is in a very high temperature operating ambient, it is impossible to directly investigate the macroscopic transport phenomena in the CC process. Thus, many researchers devoted numerical simulation to study the metallurgical behavior of CC strands. M. C. Flemings et al. first developed mathematical models for macrosegregation behavior of CC strands. Fuji et al. established the model which coupled the momentum equation with the energy equation to simulate the macrosegregation of multicomponent alloys for the first time. Spitzer et al. first developed a three-dimensional magnetohydrodynamic model, which solves the Maxwell equations and the $k$-$\varepsilon$ model equations. Poirier studied the permeability in Darcy’s law and pointed out that the composition of transverse and longitudinal resistance of permeable fluid flowing through primary dendrite arm is anisotropic, while the flow between equiaxed grains is isotropic. Bennon and Incropera employed the semi-empirical laws and principles of classical mixture theory to establish the continuous model, which described flow, heat and solute transport in binary solid-liquid phase systems.

In recent years, many researchers had studied the effect of M-EMS on the heat transfer and solidification of the flow field in the mold by means of numerical simulation. Tallback et al. numerically analyzed the influence of turbulent models parameters on flow field with M-EMS for billet CC. Natarajan and El-Kaddah adopted a fixed-grid methodology for the numerical simulation of electromagnetically driven flow in 3D inductively stirred systems and studied electromagnetic field and fluid flow with sub-mold rotary electromagnetic stirring for continuous caster of the billet. Cho et al. installed an electromagnetic shield around
the mold upper in the billet CC with M-EMS. Yu and Zhu\textsuperscript{9} simulated the fluid flow and inclusion trajectory in a round billet CC mold with M-EMS. Liu et al.\textsuperscript{10} investigated the 3D electromagnetic field, the fluid flow and the meniscus feature in a round bloom mold with M-EMS. Yang et al.\textsuperscript{11} discussed the effects of EMS parameters on the flow pattern. Ren et al.\textsuperscript{12} discovered with the increase of stirring intensity, the steady flow becomes unstable accompanying with the bias flow. Wang et al.\textsuperscript{13} discussed the effects of the current, frequency and the nozzle insertion depth on the flow field.

Some researchers\textsuperscript{6–13} did not consider the component transfer of solute elements in the mathematical model of mold macroscopic transportation. As we all know, the solute elements transfer is a very important part of macroscopic transport in CC, which determines the macrosegregation of strand. Therefore, the transfer behavior of solute elements in the mold is necessary to be studied. Kang et al.\textsuperscript{14} developed a 2D mathematical model coupling the turbulent fluid flow, heat and solute transport with an electromagnetic brake, and investigated the solidification and macrosegregation in CC of slab. Sun and Zhang\textsuperscript{15} adopted a 3D and 2D hybrid method to develop a coupling electromagnetic-thermal-solute transportation model, and investigated the macrosegregation in bloom continuous casting of steel GCr15 with EMS. Fang et al.\textsuperscript{16} numerically investigated the fluid flow, solidification and solute transport in the bloom CC with M-EMS. Zhang et al.\textsuperscript{17} developed a multi-physical-field model to predict electromagnetic field, flow field, temperature field, concentration field, and solidification profile during the initial solidification of steel billet in the CC mold with M-EMS.

All the above studies neglect the influence of the mold curvature on the transmission phenomena in the mold. However, according to the research of Trindade et al.,\textsuperscript{18} it is found that the flow field in the mold is unsymmetrical due to the mold curvature, and the inner radius presents a thinner shell. Nevertheless, the mold curvature was also neglected in the process of establishing the electromagnetic field model, which cannot avoid some errors.

On the basis of previous studies, the three-dimensional coupled models were developed to investigate electromagnetic field, flow field, heat transfer, solidification and solute transfer behavior of molten steel in vertical mold (VM) and curved mold (CM) in this paper and the simulation results under different cases were compared. Furthermore, the influence of electromagnetic and mold curvature on the macroscopic transport behaviors were also discussed.

2. Simulation Model

2.1. Assumptions

Due to the CC process with M-EMS is very complex, in order to simplify the simulation process, the current models were developed based on the following assumptions:

1. The CC process was regarded as steady state.
2. The molten steel was assumed to be incompressible Newtonian fluid.
3. The influence of mold oscillation and taper on fluid flow was neglected.
4. The mushy zone was treated as porous medium and conformed to Darcy’s law.
5. The local thermodynamic equilibrium was assumed to be always prevailed at the solid-liquid interface in the solidification process.
6. In CC process with M-EMS, because of the magnetic Reynolds number was very small and the fact that any typical angular velocity of melt was much less than the angular frequency of stirring current, the influence of melt flow on electromagnetic field was neglected. Therefore, this simulation was a one-way coupled calculation, namely, the electromagnetic field simulation was separated from the flow field calculation.
7. Owing to the Joule heating generated by the induced current was very small,\textsuperscript{12} the influence of heat generated by induced current on heat transfer was ignored.
8. The cooling water jacket, stainless steel protective jacket, and other insulation material of M-EMS were simplified to air to simulate.
9. The electromagnetic field was regarded as a quasi-static magnetic field, and the displacement current is neglected.

2.2. Fluid Flow

The fluid flow during CC process can be described by the following equations:

\[ \nabla \cdot (\rho \mathbf{u}) = 0 \] (1)

\[ \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla P + \nabla \cdot \left( \mu \nabla \mathbf{u} + \frac{2}{3} \mu \nabla \nabla \cdot \mathbf{u} \right) + \rho \mathbf{g} + \mathbf{S}_B + \mathbf{S}_M + \mathbf{F}_{\text{mag}} \ldots \] (2)

where, \( \rho \) is the density, \( \mathbf{u} \) is the flow velocity, and \( P \) is the static pressure. \( \mu \) is the effective viscosity which is equal to the sum of laminar viscosity \( \mu_l \) and turbulent viscosity \( \mu_t \). \( \mathbf{g} \) is the gravitational acceleration, and \( \mathbf{S}_B \) is the thermal-solutal buoyancy term, which is caused by temperature and concentration gradient, can be calculated by:

\[ \mathbf{S}_B = \rho g \beta_T (T - T_{\text{ref}}) + \sum m \rho g \beta_{m,\text{m}} (c_{l,m} - c_{\text{ref,m}}) \ldots \] (3)

where \( \beta_T \) is the thermal expansion coefficient, \( \beta_{m,\text{m}} \) is the solutal expansion coefficient of element \( m \), \( T \) is temperature, \( c_{l,m} \) is liquid concentration of element \( m \), \( T_{\text{ref}} \) and \( c_{\text{ref,m}} \) represent the corresponding reference value, respectively.

For the source term in Eq. (2), \( \mathbf{S}_M \) is used to describe the effect of dendritic structure on flow in mushy zone, which can be given by:

\[ \mathbf{S}_M = \frac{\mu_l}{K_p} (\mathbf{u} - \mathbf{u}_i) \] (4)

where \( \mathbf{u}_i \) is the velocity of solid, which equals to casting speed, and \( K_p \) is the permeability which can be determined by:

\[ K_p = \frac{\lambda_d^2 (f_i^3 + \xi)}{180 (1 - f_i)^2} \] (5)

where \( \xi \) is a very small positive number, which can be taken as 0.001. \( f_i \) is liquid fraction, and \( \lambda_d \) is the secondary arm space, which can be obtained by measuring the fully solidified billet.

The Low-Reynolds number \( k-\varepsilon \) turbulent model\textsuperscript{20} is adopted to describe the turbulence of melt flow in current study. The governing equations can be written as follows:

\[ \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = \nabla \cdot \left( \frac{\mu_l}{\sigma_k} \nabla k \right) + G_k - \rho \varepsilon - D + S_k \ldots \] (6)

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\[ \nabla \cdot (\rho \vec{v}) = \nabla \left[ \left( \mu + \frac{\mu_t}{\sigma_s} \right) \nabla \bar{e} \right] + C_{\text{uf}} f_i \frac{\bar{e}}{k} - C_{s2} f_2 \rho \frac{\bar{e}^2}{k} + E + S_k \quad \text{(7)} \]

where \( \mu_t = C_{\text{uf}} f_i \rho \frac{\bar{e}^2}{k} \). The Low-Reynolds number turbulent model constants and terms are listed in Table 1.

In order to reflect the effect of mushy zone on turbulence flow, the source term \( S_k \) and \( S_c \) are added to the turbulence equations, which can be expressed as:

\[ S_k = \varepsilon \mu_t / K_p \quad \text{(8)} \]
\[ S_c = k \mu_t / K_p \quad \text{(9)} \]

2.3. Heat Transfer and Solidification

The temperature field of CC process can be predicted by the following energy conservation equation:

\[ \nabla \cdot (\rho \vec{u} T) = \nabla \left[ \left( k_T + \frac{\mu_t}{\Pr_t} \right) \nabla T \right] \quad \text{(10)} \]

where \( k_T \) is thermal conductivity, \( \Pr_t \) is the Prandtl number and the value can be taken as 0.9, and \( H \) is enthalpy which can be expressed as:

\[ H = h_{\text{ref}} + \int_{t_{\text{ref}}}^{t} c_p dT + f_i \Delta H_f \quad \text{(11)} \]

where \( h_{\text{ref}} \) is reference enthalpy, \( c_p \) is specific heat, \( \Delta H_f \) is latent heat, and \( f_i \) is liquid fraction which can be represented as:

\[ f_i = \begin{cases} 0 & T \leq T_s \\ T-T_s & T_s < T < T_l \\ 1 & T \geq T_l \end{cases} \quad \text{(12)} \]

where, \( T_i \) and \( T_s \) are the liquidus temperature and the solidus temperature respectively, which can be described as follow:

\[ T_i = T_f + \sum m_m \cdot c_m \quad \text{(13)} \]
\[ T_s = T_f + \sum m_m \cdot c_m / k_m \quad \text{(14)} \]

where, \( T_f \) is melting temperature of pure iron, \( k_m \) and \( m_m \) are used to represent the equilibrium partition coefficient and liquidus slope, respectively.

2.4. Solute Transport

The conservation equation for predicting macroscopic distribution of solute elements is as follows:

\[ \nabla \cdot (\rho \vec{u} c_m) = \nabla \cdot (\rho D_{\text{eff},m} \nabla c_m) + S_c \quad \text{(15)} \]

where \( D_{\text{eff},m} \) is effective diffusion coefficient of element \( m \), which can be written by:

\[ D_{\text{eff},m} = D_{i,m} + \mu_t / \rho S_{\text{ct}} \quad \text{(16)} \]

where, \( S_{\text{ct}} = 1.0, 22 \) and \( S_c \) is the source term which can be given by:

\[ S_c = \nabla \cdot \left[ \rho (\vec{u} - \vec{u}_i) (c_{m,i} - c_m) \right] + \nabla \cdot \left[ \rho f_i D_{i,m} \nabla (c_{i,m} - c_m) \right] + \nabla \cdot \left[ \rho f_i D_{\text{eff},m} \nabla (c_{i,m} - c_m) \right] \quad \text{(17)} \]

where \( c_{i,m} \) is the solid concentration of element \( m \).

Moreover, based on the mixture theory, the concentration of element \( m \) in each computational control volume can be described by:

\[ c_m = c_{i,m} f_i + c_{l,m} f_l \quad \text{(18)} \]

Then, \( c_{i,m} \) and \( c_{l,m} \) can be written by as follow:

\[ c_{i,m} = \frac{c_m}{1 + f_i (k_m - 1)} \quad \text{(19)} \]
\[ c_{l,m} = \frac{k_m c_m}{1 + f_i (k_m - 1)} \quad \text{(20)} \]

2.5. Electromagnetic Field

In this paper, electromagnetic field is regarded as quasi-static field, which can be described by Maxwell’s equations:

\[ \begin{align*}
\nabla \times \vec{H} &= \vec{J} \\
\nabla \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t} \\
\n\nabla \cdot \vec{B} &= 0 \\
\vec{J} &= \sigma \cdot \vec{E}
\end{align*} \quad \text{(21)} \]

where \( \vec{H} \) is the magnetic field intensity, \( \vec{J} \) is the current density, \( \vec{E} \) is the electric field intensity, \( t \) is time, \( \vec{B} \) is the magnetic flux density (MFD), and \( \sigma \) is the electrical conductivity. The time-averaged electromagnetic force, which is used to describe the M-EMS force in mold, can be computed as follows:

\[ F_{\text{mag}} = \frac{1}{2} \text{Re}(\vec{J} \times \vec{B}) \quad \text{(22)} \]

where \( \text{Re} \) is the real part of a complex number.

---

**Table 1.** Low-Reynolds number turbulent model constants and terms.

<table>
<thead>
<tr>
<th>( G_t )</th>
<th>( D )</th>
<th>( f_i )</th>
<th>( f_2 )</th>
<th>( \text{Re}_t )</th>
<th>( C_a )</th>
<th>( C_{i,1} )</th>
<th>( \sigma_a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu_i \left( \frac{\partial u_i}{\partial x_i} \right) \left( \frac{\partial u_i}{\partial x_i} \right) )</td>
<td>( 2 \mu_i \left( \frac{\partial \sqrt{k}}{\partial x_i} \right)^2 )</td>
<td>( \exp \left[ -3.4 \left( \frac{1 + \text{Re}_t}{50} \right) \right] )</td>
<td>1.0</td>
<td>1.0</td>
<td>0.09</td>
<td>1.44</td>
<td>1.3</td>
</tr>
</tbody>
</table>
3. Boundary Conditions

3.1. Flow Field

The schematic illustrations and grids generation of flow field models are represented in Fig. 1. The center of the inlet was at the origin of the Cartesian coordinate system. In order to make the fully developed flow at the outlet, the computational domain was extended to the exit of foot-roller zone (This zone belongs to the secondary cooling region, where the cooling method is water spray). The mesh generation methods of the flow field models for both type molds were same, and the meshes adopted for CM are shown in Fig. 1(c). To ensure accurate simulation of the macroscopic transport behavior in the solidification front, the 15 mm wide boundary layers were divided at the boundary of the models. In this calculation, every fluid flow model contained about 666 000 meshes. The relevant technical parameters of the billet casters are listed in Table 2. The boundary conditions adopted in the flow field model are described as follows:

3.1.1. Meniscus

Considering the thermal insulation effect of mold flux, the upper surface of the model was set as the adiabatic surface, and the normal gradient of other variables was zero.

3.1.2. Inlet

The inlet velocity can be calculated by the mass conservation between the inlet and outlet, \( u_z = u_{in_z} \), \( u_x = u_{in_x} = u_y = 0 \). The inlet temperature and inlet solute element content equaled to casting temperature and steel initial content, respectively, \( T_{in} = T_c, c_{in,m} = c_{0,m} \). And that the turbulence energy and dissipation rate can be calculated using the following semi-empirical equations:\(^{23}\)

\[
\begin{align*}
    k_{in} &= 0.01 \cdot u_{in}^3 \quad \ldots \quad (23) \\
    \epsilon_{in} &= k_{in} / \nu \quad \ldots \quad (24)
\end{align*}
\]

where \( u_{in} \) is inlet velocity and \( \nu \) is inner radius of SEN.

3.1.3. Strand Surface

The wall condition was employed at strand surface, and the different types heat transfers and zero diffusive flux boundary conditions were applied. The detailed boundary conditions of heat transfers at the billet surface are given as follows:

(a) Mold zone:

\[
    q_m = 2688000 - b \sqrt{D_{loc} / \nu_c} \quad \ldots \quad (25)
\]

where,

\[
    b = \frac{1.5 \times (2680000 - q_{ave})}{\sqrt{L_{eff} / \nu_c}} \quad \ldots \quad (26)
\]

\[
    q_{ave} = \frac{C_w \times m \times \Delta T}{S_{eff}} \quad \ldots \quad (27)
\]

where \( q_m \) and \( q_{ave} \) are the heat flux and average heat flux at mold surface respectively, \( D_{loc} \) is the local distance to the meniscus, \( L_{eff} \) is the effective length of mold, \( \nu_c \) is casting speed, \( C_w \) is the specific heat of cooling water, \( m \) is cooling water flow rate in the mold, \( \Delta T \) is temperature difference between inlet and outlet water, and \( S_{eff} \) is the effective area of mold cavity.

(b) Secondary cooling zone:

\[
    q_l = h_l (T_{surf} - T_w) \quad \ldots \quad (28)
\]

where \( q_l \) is the heat flux at billet surface in secondary cooling zone, \( T_{surf} \) is the surface temperature of billet, \( T_w \) is the temperature of cooling water, and \( h_l \) is the integrative heat transfer coefficient. In this work, the secondary cooling zone only involved the foot-roller zone, so \( h_l \) can be calculated by following equation:\(^{24}\)

\[
    h_l = 165 \times w^{0.75} \quad \ldots \quad (29)
\]

where \( w \) is cooling water flow density of cooling loop in the foot-roller zone.

3.1.4. Outlet

The fully development flow boundary condition was adopted, which means that the gradients of all variables were set to zero in the normal direction.

3.2. Electromagnetic Field

To simulate the electromagnetic field of M-EMS, the corresponding electromagnetic field models of VM and CM were developed, respectively. So as to prevent the leakage of magnetic inductance lines, the M-EMS was surrounded by a cylindrical air zone. Except for the air region, each M-EMS model used about 333 000 hexahedral meshes for gridding. The meshes adopted for electromagnetic field models...
are presented in Fig. 2. Three-phase exciting current was applied to the winding coil of the M-EMS, and the phase difference of the current was 120°. The magnetic induction lines on the boundary of the model were defined to be parallel to the boundary plane of the air region.

3.3. Technological and Thermophysical Parameters

The equilibrium partition coefficients, slope of liquidus line, and solutal expansion coefficients for different solute elements recommended by Ueshima et al.25) and Jie et al.26) are listed in Table 3. Meanwhile, the steel initial content employed in this calculation and subsequent plant trial also are shown in Table 3. Moreover, Table 425) gives the diffusion coefficients for different solute elements.

In this paper, the technological parameters were obtained from a factory in North China. In addition, some related thermophysical parameters were calculated by software JMatPro (Sente Software Ltd., Surrey, U.K.), and the others were derived from published literatures.10,27–29) The technological parameters and thermophysical parameters are listed in Table 5.

The thermal conductivity and viscosity are very important thermophysical parameters to predict the flow and solidification behavior of molten steel, especially for the mushy zone. Some researchers27,18,30) regarded them as constants, but in fact, the thermal conductivity and viscosity change significantly with local temperature (or local liquid fraction). Figures 3 and 4 shows the variations of thermal conductivity and viscosity with temperature, respectively, which were calculated by software JMatPro. Moreover, the relationship between the liquid fraction and temperature is also presented in Fig. 4. It is seen that the viscosity in mushy zone is obviously higher than that in liquid region.

4. Solution Procedure

In this paper, the simulation processes were split into two stages: First, the finite element software ANSYS (ANSYS Inc., Canonsburg, PA) was adopted to calculate the distributions of electromagnetic force in VM and CM, respectively; second, the electromagnetic force was imported into the fluid model of the VM and CM by UDF (user defined functions) of software Fluent (Fluent Inc., New York, NY) as momentum source to simulate the coupling of flow, heat transfer, solidification, mass transfer. When the fluid velocity and temperature of the monitoring point at the outlet no

| Table 3. Initial content and related parameters for different solute elements. |
|-----------------|-----------------|-----------------|-----------------|
| Element         | \(c_{\text{eq}}(\text{wt\%})\) | \(k_{\alpha,25}(\text{\degree C}^{-1})\) | \(m_{\alpha,25}(\text{K/\text{wt\%}})\) | \(\beta_{\alpha,25}(\text{\text{wt\%}})\) |
| C               | 0.71            | 0.34            | -78.0           | 1.10 \times 10^{-2} |
| Si              | 0.22            | 0.52            | -7.6            | 1.19 \times 10^{-2} |
| Mn              | 0.55            | 0.78            | -4.9            | 1.92 \times 10^{-3} |
| P               | 0.01            | 0.13            | -34.4           | 1.15 \times 10^{-2} |
| S               | 0.004           | 0.035           | -38.0           | 1.23 \times 10^{-2} |

| Table 4. Diffusion coefficients for different solute elements. |
|-----------------|-----------------|-----------------|
| Element         | \(D_{\alpha,25}(\text{cm}^2/\text{s})\) | \(D_{\alpha,25}(\text{cm}^2/\text{s})\) |
| C               | 0.0052 \times -11 700/RT | 0.0761 \times -134 557.44/RT |
| Si              | 0.000514 \times -9 150/RT | 0.3 \times -251 458.4/RT |
| Mn              | 0.00308 \times -16 600/RT | 0.055 \times -249 366.4/RT |
| P               | 0.0135 \times -23 700/RT | 0.01 \times -182 840.8/RT |
| S               | 0.00049 \times -8 600/RT | 2.4 \times -223 425.6/RT |

| Table 5. Technological parameters and thermophysical parameters. |
|-----------------|-----------------|
| Items           | Value/unit      |
| Casting speed   | 1.8 m/min       |
| EMS coil current| 300 A           |
| Frequency of EMS source current | 3 Hz |
| Casting temperature | 1 771 K |
| Cooling water flow rate of cooling loop in the foot-roller zone | 58.4 L/min |
| Density of steel | 7.220 kg/m³ |
| Specific heat capacity | 650 J/kg·K |
| Thermal expansion coefficient | 2.0 \times 10^{-4} \text{K}^{-1} |
| Latent heat     | 235 730 J/kg   |
| Fusion temperature of pure iron | 1 808 K |
| Electrical conductivity of steel | 7.14 \times 10^{-3} \Omega^{-1} \text{m}^{-1} |
| Electrical conductivity of copper mold | 4.7 \times 10^{7} \Omega^{-1} \text{m}^{-1} |
| Magnetic permeability of the vacuum | 3.18 \times 10^{7} \text{H/m} |
| Relative permeability of iron core | 1.257 \times 10^{-4} \text{H/m} |
| Relative permeability of air, molten steel, coil copper mold, or stainless-steel shell | 1.0 |
longer changed, it was considered that the simulated CC process achieves steady state. In order to better observe the simulation results, the aspect ratio of the displayed results was adjusted in the post-process.

5. Results and Discussion

5.1. Electromagnetic Field

For the purpose of validating the electromagnetic field model in this paper, the magnetic flux density (MFD) was measured by using a SHT-III Teslameter (HP Spinix Inc., Shenyang, CN). Figure 5 presents the calculated and measured value variations of MFD under \( I = 300 \) A and \( f = 3 \) Hz on center-line along the casting direction. It is seen that the distribution of the simulated MFD agrees well with measured under the assumption of the copper tube temperature is 298 K (under non-production), so it can be considered that the electromagnetic field model is credible. Furthermore, the temperature of copper tube has a great influence on the MFD, which is the predicted MFD under temperature of copper tube is 298 K is greater than 423 K\(^{15,27}\) (under actual production). This can be interpreted as the conductivity of copper tube varies with the temperature, so that the copper tube has relatively weaker electromagnetic shielding effect at higher temperature. In the following simulations, the temperature of mold copper tube was set to 423 K.

Moreover, it should be pointed out that above verification can only verify the reliability of the electromagnetic field model for CM. However, due to the predicted distribution profiles of MFD for VM and CM are basically coincident and it is just that there is a slight difference at the lower part of mold, as shown in Fig. 5 and enlarged plot, which also indirectly proves the rationality of the electromagnetic field model for VM. This way is in agreement with other researchers.\(^{11,15,17}\)

Figure 6 shows distributions of electromagnetic force of \( X = 0 \) plane under \( I = 300 \) A and \( f = 3 \) Hz for different type molds, where \( X \) is X-direction coordinates in Cartesian coordinate system. It is seen that the electromagnetic force is mainly distributed in the M-EMS region for VM and CM. The maximum electromagnetic force is located at the surface of the billet of the stirrer center. Meanwhile, the electromagnetic force decreases radially from the surface to the interior the billet. In short, the distribution of electromagnetic force is basically the same for VM and CM.

Figure 7 presents the profiles of electromagnetic force...
along the center-line of the stirrer mid-plane. It is shown that the curves of electromagnetic force for VM and CM are approximately the coincidence, that both decrease linearly from the surface to the center of the billet. However, the electromagnetic force is presented slightly smaller on the inner curve side (ICS) for CM, which is due to the ICS of billet is further away from the iron core of stirrer.

Figure 8 displays distributions of Joule heating power density of $X = 0$ plane under for different type molds. It is seen that the Joule heating power density is also mainly distributed in the M-EMS region, and the closer to the billet surface, the greater the value. Calculated by volume integral, the total Joule heat generated by the induced current of the whole computational domain is only about 12.1 W, which is far less than the mold heat flow (about 868.8 KW). Therefore, it is reasonable to ignore the effect of heat generated by inducted current on heat transfer.

5.2. Melt Flow

Figure 9 shows the 3-D streamlines plot of flow field for different cases. It is observed that the 3-D streamlines plots are significantly different for VM and CM. Regardless of M-EMS turned-off ($I = 0$ A) or turned-on ($I = 300$ A), there is an axisymmetric flow in the VM, but a non-axisymmetric flow in the CM. When M-EMS is off, the jet flow entering through SEN produces circulation flow in the upper part of the mold due to the continuum of the fluid, while the flow direction in the lower part of the mold parallels to the casting direction. Whereas for CM, the obvious circulation flow only appears on the ICS, and few streamlines in 0–0.3 m zone away from the meniscus of the outer curve side (OCS), which can be called “dead zone” in this region. When the M-EMS is on, counter-clockwise swirl flow is produced in both type molds, and that the streamlines in the lower part of the mold also present a spiral shape. For CM, although the swirl flow is non-axisymmetrical, the molten steel in the mold is also stirred fully, making the “dead zone” disappear.

Figure 10 lists the melt flow patterns at the mid-plane of stirrer for different cases. It is observed that no matter...
the M-EMS is off or on, the velocity distribution for VM is axisymmetrical and that for CM is non-axisymmetrical. For VM, when M-EMS is off, the maximum velocity is located at the center of mid-plane, while the velocity is low at other locations. When M-EMS is on, the counter-clockwise swirling flow is produced, making the flow velocity of entire cross-section become greater, and the vortex core positions at the center of the mid-plane. But for CM without M-EMS, the maximum velocity is not located at the center of the mid-plane, but get closer to the OCS. In the presence of M-EMS, the position of maximum velocity deflects along the direction of swirling flow and deviates from the center of the mid-plane. At the same time, the vortex core also deviates from the center of the mid-plane and approaches the OCS. The velocity in the outer regions of the melt is relatively small, it is about \(0.03 \text{ m/s}\) which consistent with casting speed. This is because the regions correspond to the mushy zone and solidified shell, and the electromagnetic force has little or no effect on mushy zone or solidified shell. The evaluation of stirring intensity can be characterized by the tangential velocity, when the electromagnetic force causes swirling flow under M-EMS. Figure 10 shows the tangential velocity profiles along the center-line of stirrer mid-plane It is seen that when without M-EMS, the tangential velocity is almost 0 for VM and CM. When the M-EMS is applied, the tangential velocity decreases from the solidification front to the center of the billet, but the change laws for both types of mold are different. For VM, the tangential velocities of both sides are identical, which approximatively linearly reduces from the solidification front to the center of the billet, and the maximum tangential velocity is 0.13 m/s. For CM, the variation curve of tangential velocity from the solidification front of ICS to that of OCS displays a wave shape, this is different from the VM. In addition, the tangential velocity on the ICS is greater than on the OCS for CM, and the maximum tangential velocity is 0.16 m/s and 0.12 m/s, respectively. From the above it can be seen that the mold curvature has a significant effect on the mold flow field, which will affect the macroscopic transport phenomenon in the mold. In view of this, in the process of establishing the numerical model of the macroscopic transport phenomenon in the mold for curved caster, the mold curvature cannot be ignored.

It should be noted the magnetic Reynolds number in this calculation is about 0.007 which is small enough, so that the motion of the molten steel has a minimal impact on the magnetic flux density. Meanwhile, the maximum angular velocity of molten steel is about 1.8 rad/s of molten steel and the angular frequency is about 10 times the maximum angular velocity, therefore the influence of rotational motion on electromagnetic force can be ignored. In short, the assumption 6 is considered feasible.

5.3. Heat Transfer and Solidification

Figure 12 shows the distributions of temperature field of \(X = 0\) plane for different cases. It is shown the high temperature zone of molten steel is located at the jet region, and the temperature decreases along the casting direction for VM and CM. Whereas due to the mold curvature, the distribution of temperature field is symmetrical for VM, but is non-symmetrical for CM and the hot jet deflects to the OCS. For CM without M-EMS, it is seen that there exists a low temperature zone which coincides with position of “dead zone”. As M-EMS is applied, the low temperature zone disappears with the disappearance of “dead zone”. In addition, the application of M-EMS is conducive to reducing the temperature of liquid core in lower part of model for VM and CM. Especially for CM, the isotherm of \(X = 0\) plane in lower part of the model move up obviously, as shown Fig. 12(d). According to the reports, the M-EMS is beneficial to improve the heat transfer efficiency, thus speeding up the release of superheat of molten steel in the mold. Meanwhile, the M-EMS can weaken the invasion depth of the jet, preventing higher melt flow from injecting the liquid core. It is well known that the low temperature casting advantageous to improve the central equiaxed grain rate, thereby improving the core quality of billet and reducing the central segregation. For further illustrate the effect of M-EMS on the temperature of melt, the variations of center temperature along the casting direction for different cases are displayed in Fig. 13. It is seen that the center
temperature of the billet decreases gradually with increase of distance from the meniscus. The enlarged plot also shows that the liquid core temperature at the outlet of model with M-EMS is lower than that without M-EMS. Moreover, when M-MES is on, the outlet center temperature for CM is significantly lower than that for VM. The main reason for this difference is that the stirring intensity is not large enough in this calculation, the effect of M-EMS on reducing the invasion depth of hot jet is not obvious for VM. While for CM, due to the mold curvature and the flow field is non-symmetrical, the M-EMS deflects the direction of hot jet, as shown in Fig. 12(d), which shortens the effective invasion depth of hot jet and is conducive to the reduction of liquid core temperature.

Figure 14 gives the variations of shell thickness along the casting direction for different cases. The solidified shell can be considered as liquid fraction is 0.3. \(^{22}\) It is seen that with the increase of the distance from the meniscus, the solidified shell thickness increases for all cases. In the region 0–0.3 m from the meniscus, the growth rules of the solidified shell are basically the same for all cases. However, at the model exit, the solidified shell under the M-EMS is thicker than when M-EMS is off, as displayed in the enlarged plot. This is different from the research results of some authors,\(^ {11,17} \) they affirmed that the solidified shell grows slowly or stagnates due to the washing effect of stirring flow generated by M-EMS. But on the other hand, the M-EMS can improve the heat transfer efficiency and accelerate heat release, so it can be said that M-EMS plays a role of cooler.\(^ {32} \) In this work, the intensity of M-EMS is not enough strong, so that the reduction of shell thickness induced by washing effect is less than the increase of shell thickness caused by improving heat transfer efficiency and prolong residence time of molten steel in the mold. Furthermore, the washing effect of the solidification front is intensified for with M-EMS to reduce the solute content at the solidification front, which leads to the raise of local solidification temperature, according to Eq. (14), so that the local molten steel can be solidified at a higher temperature. In conclusion, the application of M-EMS is more conducive to shell growth in this paper. For CM, the thickness of shell on the ICS is slightly larger than that on the OCS. This is due to the hot jet deflects to the OCS, the solidified shell on the OCS is scoured by the hot jet, making the solidified become thin. It is observed

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**Fig. 12.** Distributions of temperature field of \( X = 0 \) plane for different cases, (a) VM with \( I = 0 \) A, (b) VM with \( I = 300 \) A, (c) CM with \( I = 0 \) A, (d) CM with \( I = 300 \) A. (Online version in color.)

**Fig. 13.** Variations of center temperature along the casting direction for different cases. (Online version in color.)

**Fig. 14.** Variations of shell thickness along the casting direction for different cases. (Online version in color.)
from Fig. 14 that the curve of the shell thickness on the OCS under the M-EMS is obviously lower than other curves in the region of 0.3 m–0.5 m distance from the meniscus, this due to the scouring effect on the OCS shell is more obvious in the presence of M-EMS. Below 0.5 m from meniscus, due to M-EMS can accelerate the release of superheat of the molten steel, the solidified shell thickness on the OCS and ICS with M-EMS are thicker than that without M-EMS on the corresponding sides.

5.4. Distributions of Solute Elements

Figure 15 shows the distributions of solute elements of \( X = 0 \) plane with M-EMS for CM. It is seen that the predicted distributions of C, Si, Mn, P, and S are similar, which is consistent with previous studies.\(^{15,31,33} \) Based on this, only the distribution of the solute element C is discussed below.

Figure 16 presents the distributions of solute element C of \( X = 0 \) plane for different cases. It is seen that the distribution of solute element C is symmetrical for VM, but non-symmetrical for CM. For VM, it is observed that as the molten steel solidifies continuously, the solute elements are rejected from the initial solidified shell into the bulk liquid, that due to the solubility of elements in solid phase is less than that in liquid phase, so that the solute elements are enriched in the liquid phase. Also, it is noticed that the solute element C enrich at the mold top near the meniscus, and the negative segregation of element C appears at the zone below 0.25 m away from the meniscus near the billet surface. The reason for the results is the solute-richer melt at the solidification front is flowed toward the top of the mold by upwelling, and thus the solute content at the solidification front decreases. This process can be called washing effect. And then the solute-richer melt finally gathers near the meniscus due to the washing effect of upwelling. Therefore, the element C appears positive segregation in the initial solidified shell. However, due to the washing effect, the solute content at the solidification front in the region below 0.25 m away from meniscus becomes lower, so negative segregation of element C emerges in the subsequent generating solidified shell. For CM, the mechanism of non-uniform element C distribution in it is same as that for VM. However, due to the non-symmetrical distribution of the flow field, the solute element C distribution on ICS and on OCS are different. The negative segregation on the OCS appears farther away from the meniscus than on the ICS and negative segregation band on the OCS is narrower than on the ICS. This phenomenon can be explained that the solute-richer melt at the solidification front on the ICS is affected by washing effect is stronger than on the OCS, as shown in Fig. 9(c). In addition, there is a “dead zone” of flow field, so solute elements also gather here, which is presented in Fig. 16(c). When M-EMS is applied, the distribution of solute element C also changes due to the varies of flow field. The position of negative segregation on the OCS moves up but that on the ICS moves down, as displayed in Fig. 16(d). Meanwhile, due to the “dead zone” disappears, the solute-richer zone on the OCS disappears.

Figure 17 presents the segregation degree profiles of solute element C along the center-line of the cross-section at model outlet. It is seen that the segregation degree of element C on the surface of billet is different between VM and CM, but the distribution trend is basically the same. For VM, the maximum positive segregation occurs at the billet surface. While for CM, the peak positive segregation

![Fig. 15. Distributions of solute elements of \( X = 0 \) plane with M-EMS for CM, (a) C, (b) Si, (c) Mn, (d) P, (e) S. (Online version in color.)](image-url)
emerges at about 4 mm distance from the billet surface of both sides. For both type molds, it decreases sharply with the distance from the billet surface after element C reaches maximum positive segregation degree, and the minimum negative segregation occurs at about 10 mm away from the billet surface. The element C which is larger than the nominal concentration of liquid core again. The reason for the oscillation of C element content at the central line is mainly due to circulation flow in upper part of mold, which has been analyzed above.

In order to verify accuracy of the model, a cross-sectional billet sample was taken for composition analysis. The experimental conditions, such as caster information, process parameters and steel composition, are consistent with the data adopted to establish the model and have been listed in Tables 2, 3 and 5, respectively. Subsequently, the Φ2 mm drill was used to extract steel scraps at the positions of 0 mm, 5 mm and 10 mm distance from the both curved sides along the centerline of cross section. Then the element C concentration of scraps at different drilling positions was determined by Carbon-Sulfur Analyzer (LECO Corporation, St. Joseph, MI). The measured results are also plotted in the Fig. 17. It is shown that the predicted results agree well with the measured results, therefore confirming the validity of present model developed in this study.

6. Conclusions

In this paper, a three-dimensional coupled model has been developed to investigate the flow, heat transfer, solidification, solute transport and electromagnetic field for the vertical mold and the curved mold, respectively. The main conclusions are as follows:

(1) The electromagnetic force is mainly distributed in the area of the M-EMS, and the distribution laws of electromagnetic force are similar for vertical mold and curved mold, which are linearly reduced from the billet surface to the center. Moreover, due to curvature, the maximum value of the electromagnetic force on the inner curve side of the curved mold is slightly less than vertical mold.

(2) Whether M-EMS is applied or not, the distributions of flow, temperature and solute elements are symmetrical for vertical mold, but non-symmetrical for curved mold. It can be seen the curvature of the mold has a great influence on the macroscopic transmission behavior in the mold, so the mold curvature cannot be ignored during studying macroscopic transmission behavior in the mold.

(3) Under the condition of M-EMS, the rotating flow is generated in the mold, which makes the molten steel fully stirred. But for curved mold, the vortex core is not located at the mid-plane center of the stirrer.

(4) The M-EMS can enhance the superheat dissipation of the molten steel to reduce liquid core temperature and promote the growth of solidification shell. For curved mold, the solidified shell on outer radius side presents a thinner shell.

(5) As the result of washing effect of flow at the upper part of the mold, the positive segregation of elements emerges on the surface of the billet, and the negative segregation band appears at the subsurface of the billet. The C...
element segregation degree of predicted results agree well with the measured and thus verify the rationality of the coupled model.

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Conflict of Interest
The authors declare no conflict of interest.

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