A transient three-dimensional (3D) mathematical model has been established to study the effect of the current on the desulfurization in the electroslag remelting process using direct current (DC). The solutions of the mass, momentum, energy, and species conservation equations were simultaneously calculated by the finite volume method. The movement of the metal droplet was described by the volume of fluid (VOF) approach. In order to include the influences of the slag composition and the current on the desulfurization, a dynamic module was introduced. Three experiments have been carried out to validate the model. The volume-average temperature of the slag increases from 1 940 K to 2 019 K, while the current ranges from 1 200 A to 2 400 A. The sulfur transfer caused by the slag treatment is promoted by the stronger current because of the higher temperature. The value of the negative transfer rate induced by DC also becomes larger with the increasing of the current. The overall transfer rate at the metal droplet-slag interface is decided by the competition of these two transfer rates. The removal ratio of sulfur increases from 82% to 88% when the current changes from 1 200 A to 1 500 A, and then drops to 65% if the current continuously increases to 2 400 A.

KEY WORDS: electroslag remelting; desulfurization; MHD two-phase flow; heat transfer; numerical simulation.
Butler-Volmer model for the kinetics of the heterogeneous electrode reactions was used to obtain the faradaic current density, and moreover the interplay of Lorentz force, convection and redox species concentration distribution was studied.

As discussed above, there have been no attempts to numerically investigate the effect of the current on the desulfurization behavior in the ESR process. Because of this, the authors were motivated to establish a transient 3D comprehensive model to understand the influence of the current on the sulfur transfer in a small DC ESR furnace. The electromagnetic, flow and temperature fields were included. The desulfurization rate was simultaneously solved using a dynamic module. In addition, three experiments were implemented to validate the model.

2. Mathematical Model

2.1. Assumptions

The following assumptions have been proposed to simplify the model:

1. The domain included the molten slag and the molten metal. The air and the solidified metal were ignored.\(^{13}\)
2. The two fluids were incompressible Newtonian fluid. The densities of the slag and the metal were a function of the temperature. The slag electrical conductivity depended on the temperature. The other properties of the slag and the metal were assumed to be constant.\(^{12}\)
3. The slag and the metal were assumed to be electrically insulated from the mold.
4. Other elements were ignored except sulfur.

2.2. MHD Two-Phase Flow and Heat Transfer

As mentioned above, there were two phases in the furnace, and the current traveled through the two phases. The Joule heating and magnetic field were then created by the current. The interaction between the magnetic field and the current gave rise to an inward Lorentz force. The Joule heating and magnetic field were then created by the current. The Joule heating maintained the thermal balance of the furnace. The slag and the metal were driven to flow under the combined effect of Lorentz and buoyancy forces.

A module about the MHD two-phase flow and heat transfer was invoked in the present work, and the details of the module could be found in Ref. 4). Only a basic description would be given here. In the model, the finite volume method was used to simultaneously solve the mass, momentum and energy conservation equations. The Joule heating and Lorentz force were fully coupled through solving the Maxwell’s equations with the assistance of the magnetic potential vector. The redistribution of the two phases was described by the VOF approach. The RNG k-ε turbulence model, which is able to capture the behavior of flows with lower Reynolds numbers, was employed to calculate the turbulent viscosity. An enhanced wall function was used to work with the RNG k-ε turbulence model.

2.3 Mass Transfer of Sulfur

Sulfur in the metal could be transferred into the slag because of the chemical reaction at the slag-metal inter-face. Meanwhile, the convection and diffusion of sulfur in the slag and the metal promoted the desulfurization. These phenomena were represented by:\(^{13-15}\)

\[
\frac{\partial (\tilde{\rho}_S)}{\partial t} + \nabla \cdot (\tilde{\rho}_S \mathbf{v}_S) = \nabla \cdot \left( \alpha \mathbf{D} \frac{\mathbf{c}}{T} \right) + S \quad \ldots (1)
\]

The equation was established in the slag and the metal, respectively, and the two equations were calculated at the same time. The source term indicated the mass transfer rate of sulfur at the slag-metal interface. In order to satisfy the mass conservation, the source terms in the two equations were numerically equal but opposite in sign.

2.4. Dynamic Module

An auxiliary dynamic module was developed to estimate the reaction rate. The desulfurization could be expressed:

\[
[S] + 2e = (S^{2-}) \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots
The oxygen activity in the metal, \( a_{[O]} \), was supposed to be influenced by the dissolved aluminum and oxygen in the bulk of the metal and the alumina in the slag according to the reaction:

\[
2[\text{Al}] + 3[\text{O}] = (\text{Al}_2\text{O}_3) \]  

The equilibrium constant for this reaction could be expressed:  

\[
\log K = \log a_{[\text{Al}_2\text{O}_3]} - \frac{a_{[\text{Al}]}^2}{a_{[O]}} = \frac{45 300}{T} - 11.62 \quad \text{(7)}
\]

where \( a_{[\text{Al}]} \) was the aluminum activity in the metal, which was estimated by the aluminum activity coefficient:

\[
a_{[\text{Al}]} = f_{[\text{Al}]} \cdot w[\text{Al}] \quad \text{(9)}
\]

Substituting Eq. (9) into Eq. (8), \( a_{[\text{Al}]} \) therefore was rewritten as:

\[
\log a_{[\text{Al}]} = \frac{1}{3} \log a_{[\text{Al}_2\text{O}_3]} - \frac{2}{3} \log w[\text{Al}] - \frac{15 100}{T} + 3.87 \quad \text{(10)}
\]

The aluminum activity coefficient, \( f_{[\text{Al}]} \), was calculated using Eq. (6). \( a_{[\text{Al}_2\text{O}_3]} \) was the alumina activity in the slag, which varies with the temperature. According to our previous studies, the slag temperature in the ESR process was mainly within the range of 1 900 K to 2 200 K.\(^4\,12\))

Table 1 provided the thermodynamic commercial software FactSage was then adopted to estimate the evolution of the \( a_{[\text{Al}_2\text{O}_3]} \) within this temperature range. A fitting function was proposed:

\[
a_{[\text{Al}_2\text{O}_3]} = 0.3 - 3.99342e^{-0.0018T} \quad \text{(11)}
\]

Now let us considered the electrons provided by the current. According to the electrode reaction, the mass transfer rate of sulfur was related to the intensity of the electron flow:  

\[
S_s = \pm \frac{j}{nF} M_s \quad \text{(12)}
\]

where \( j \) was the magnitude of the local current density. \( n \) referred to the number of the electrons entering in the reaction (in this case \( n = 2 \)). \( M_s \) was the molar mass of sulfur. Moreover, the rate would have a positive or a negative sign, which depends on the movement direction of the electron. When the electrons flow from the metal to the slag, sulfur in the metal would capture two electrons and then enter into the slag as sulfur ion. The sulfur content in the metal therefore reduces, and the rate is positive. But if the electrons migrate in an opposite direction, sulfur in the slag would go into the metal as sulfur atom but lose two electrons. As a result, the sulfur concentration in the metal rises, and the rate is negative.\(^3\,25\))

2.5. Boundary Conditions

The boundary conditions used for the MHD two-phase flow and heat transfer module could be found in Ref. 4). As for the desulfurization process, a constant mass percent of sulfur was applied at the electrode tip, and sulfur was allowed to flow out from the bottom. Additionally, a zero flux was used at the wall. The detailed physical properties and the geometrical condition were listed in Table 1, and the compositions of the electrode and the slag were displayed in Table 2.

### Table 1. Physical properties of metal and slag, and geometrical conditions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical properties of metal</td>
<td></td>
</tr>
<tr>
<td>Reference density, kg/m(^3)</td>
<td>7.500</td>
</tr>
<tr>
<td>Viscosity, Pa·s</td>
<td>0.0061</td>
</tr>
<tr>
<td>Latent heat of fusion, kJ/kg</td>
<td>270</td>
</tr>
<tr>
<td>Thermal conductivity, W/m·K</td>
<td>30.52</td>
</tr>
<tr>
<td>Specific heat, J/kg·K</td>
<td>752</td>
</tr>
<tr>
<td>Electrical conductivity, Ω(^{-1})·m(^{-1})</td>
<td>7.14×10(^{2})</td>
</tr>
<tr>
<td>Magnetic permeability, H/m</td>
<td>1.257×10(^{-4})</td>
</tr>
<tr>
<td>Thermal coefficient of cubical expansion, K(^{-1})</td>
<td>1.1×10(^{-4})</td>
</tr>
<tr>
<td>Physical properties of slag</td>
<td></td>
</tr>
<tr>
<td>Reference density, kg/m(^3)</td>
<td>2.800</td>
</tr>
<tr>
<td>Viscosity, Pa·s</td>
<td>0.025</td>
</tr>
<tr>
<td>Thermal conductivity, W/m·K</td>
<td>10.46</td>
</tr>
<tr>
<td>Specific heat, J/kg·K</td>
<td>1.255</td>
</tr>
<tr>
<td>Electrical conductivity, Ω(^{-1})·m(^{-1})</td>
<td>ln(\sigma) = -6 769/T + 8.818</td>
</tr>
<tr>
<td>Magnetic permeability, H/m</td>
<td>1.257×10(^{-4})</td>
</tr>
<tr>
<td>Thermal coefficient of cubical expansion, K(^{-1})</td>
<td>5.4×10(^{-4})</td>
</tr>
<tr>
<td>Geometry</td>
<td></td>
</tr>
<tr>
<td>Electrode diameter, m</td>
<td>0.055</td>
</tr>
<tr>
<td>Mold diameter, m</td>
<td>0.12</td>
</tr>
<tr>
<td>Slag pool height, m</td>
<td>0.06</td>
</tr>
<tr>
<td>Metal pool height, m</td>
<td>0.03</td>
</tr>
</tbody>
</table>

### Table 2. Compositions of the electrode and the slag.

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass percent, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrode</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.08</td>
</tr>
<tr>
<td>Si</td>
<td>0.75</td>
</tr>
<tr>
<td>Mn</td>
<td>1.8</td>
</tr>
<tr>
<td>Cr</td>
<td>16.58</td>
</tr>
<tr>
<td>P</td>
<td>0.008</td>
</tr>
<tr>
<td>S</td>
<td>0.011</td>
</tr>
<tr>
<td>Ni</td>
<td>5.14</td>
</tr>
<tr>
<td>Mo</td>
<td>2.38</td>
</tr>
<tr>
<td>Fe</td>
<td>Bal.</td>
</tr>
<tr>
<td>Slag</td>
<td></td>
</tr>
<tr>
<td>CaF(_2)</td>
<td>70</td>
</tr>
<tr>
<td>Al(_2)O(_3)</td>
<td>30</td>
</tr>
</tbody>
</table>
3. Solution Procedure

The commercial software ANSYS-FLUENT 12.1 was employed to run the simulation. The governing equations for the electromagnetism, two-phase flow, heat transfer and solute transport were integrated over each control volume and solved simultaneously, using an iterative procedure. The introduction of the magnetic potential, the coupling between the Joule heating and the energy equation, and the coupling between the Lorentz force and the momentum equation were achieved by user defined functions. The development of the dynamic module was also accomplished by our own program. The widely used SIMPLE algorithm was employed for calculating the Navier-Stokes equations. All the equations were discretized by the second order upwind scheme for a higher accuracy. Before advancing, the iterative procedure continued until all normalized unscaled residuals were less than $10^{-6}$. The physical domain was discretized with a structured mesh. Mesh independence was thoroughly tested. Three families of meshes were generated with 150,000, 311,000, and 520,000 control volumes, respectively. After a typical simulation, we carefully compared velocity and temperature of some points in the domain. The deviation of simulated results between the first and second mesh is about 8 pct, while approximately 3 pct between the second and third mesh. Furthermore, the value of $y^+$ within the first layer grid of the three meshes was equal to $\sim 1$. Therefore, considering the expensive computation, the second mesh was retained for the rest of the present work. Figure 1 shows the mesh and boundaries. Due to the complexity of the coupling calculation, the time step was kept small to ensure that the above convergence criteria were fulfilled. Using 8 cores of 4.0 GHz, one typical case’s calculations took approximately 140 CPU hours.

4. Experiment

Three experiments were carried out using a mold with an open air atmosphere. The inner diameter, height, and mold wall thickness were 120 mm, 600 mm and 65 mm. The currents used in the experiments were 1,200 A, 1,800 A and 2,400 A, respectively. The consumable electrode was the AISI 201 stainless steel with a 55 mm diameter. The electrode was employed as the positive pole in the tests, while the negative pole was the baseplate. The slag composition was calcium fluoride, 70 mass pct, and aluminum oxide, 30 mass pct, and the weight of the slag was about 2.3 kg. The slag temperature was measured every 5 minutes by a disposable W3Re/W25Re thermocouple. Moreover, a sample was taken from the slag every 5 minutes, and the mass percent of sulfur in the slag specimen was analyzed by a carbon sulfur analyzer.

5. Results and Discussions

Figure 2 illustrates the electric streamlines and phase distribution at 1,020 s with a current of 1,800 A. As stated above, the inlet is the positive pole, and the bottom is the negative. The electric current therefore flows downward from the electrode tip and moves to the outer edge of the slag layer. The movement of the current is influenced by the metal droplet because of the higher electrical conductivity. It is obvious that the current tends to enter into the metal droplet. Current slightly converges in the upper part of the droplet, and diverges in the lower part. Figure 3 represents the flow pattern and the temperature distribution. Two pairs of vortexes are found in the slag. The heat extracted by the cooling water results in a descent

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**Fig. 1.** (a) Mesh, and (b) boundaries. (Online version in color.)

**Fig. 2.** Distributions of the electric streamlines and the two fluids at 1,020 s with a current of 1,800 A. (Online version in color.)
of the slag in the vicinity of the lateral wall. A stable clockwise circulation is clearly observed in the right side of Fig. 3. As stated above, the interaction between the self-induced magnetic field and the current generates an inward Lorentz force. Therefore, a counterclockwise cell is created by the Lorentz force and the falling droplet at the center of the slag.

The Joule heating is supposed to be determined by the current density and the electrical resistivity. The electrical resistivity of the slag is supposed to be 10³ times larger than that of the metal. Consequently, most Joule heating is created in the slag layer, and thus the slag is much hotter than the metal. Due to a higher current density, greater Joule effect is generated around the electrode tip. A higher temperature region is clearly observed at the top slag layer and around the outer side of the electrode tip.

Figure 4 displays the comparison of the temperature between the simulations and the measurements. An acceptable agreement was obtained. The discrepancies that exist can be explained by the uncertainty about the thermal boundary conditions as well as the material properties.

On the other hand, the temperature difference between the slag layer and the metal pool drives the metal along the slag-metal pool interface toward the outer edge and, from there, down along the wall. Lots of heat is therefore transferred to the cooling water. The temperature of the metal at the middle of the mold is higher than that at the two sides.

Figure 5 indicates the distribution of the sulfur mass percent in the metal at different time instants. The desulfurization occurs at the slag-metal interface during the droplet formation. As a result, the metal close to the droplet surface has a lower sulfur concentration as shown in Fig. 5(a). The droplet grows bigger with a balance of Lorentz force, surface tension force and gravity. After a neck is formed, the velocity within the droplet increases due to the increased Lorentz pinch force at the neck. The droplet is then detached and falls into the metal pool as demonstrated in Fig. 5(b). We can see that the sulfur concentration in the center of the droplet is higher than that in the outside layer. When the droplet hits the metal pool-slag interface, sulfur quickly spreads out in the metal pool, and its distribution is controlled by the flow pattern as displayed in Fig. 5(c).
The flow of the metal drags sulfur moving to the outer side of the mold along the interface. Due to the influence of the cooling water, sulfur then turns downward at the wall, and finally flows out from the outlet. Results indicate that the sulfur transfer occurred over a relatively short time in the order of seconds, and the formation of the droplet occupies most of the time. It can be concluded that the desulfurization is mostly achieved during the droplet formation.

Figure 6 illustrates the mass percent distribution of sulfur in the slag. It is obvious that the slag in the vicinity of the electrode tip always has the highest sulfur concentration. Due to the fluid flow, sulfur would be fast expanded to the rest of the slag pool. Besides, the sulfur content in the slag that around the metal droplet remarkably rises during the falling of the droplet. Sulfur then moves upward under the effect of the wake stream of the droplet. Meanwhile, sulfur in the metal pool would be transferred into the slag through the metal pool-slag interface. Hence, a higher content of sulfur is observed in the slag near the interface after the droplet falls into the metal pool.

As described above, there are two mechanisms for the desulfurization. Part of the electrons involved in the reaction were provided by the oxygen ion in the slag. The corresponding mass transfer rate is shown in Fig. 7(a), which is greatly affected by the temperature, the sulfur concentration difference and the slag composition. It is obvious that the transfer rate of the upper interface, i.e. the metal droplet-slag interface, is larger than that of the lower interface, i.e. the metal pool-slag interface. It is mainly because that the upper slag is hotter than the lower one, and moreover the concentration difference of sulfur close to the electrode tip is higher.

Figure 7(b) represents the mass transfer rate induced by the DC, and its sign is determined by the motion direction of the electron. The current flows from up to down in the furnace, and thus the electrons move in the opposite direction. At the metal pool-slag interface, the electrons move from the metal to the slag. Sulfur in the metal would capture two electrons and enter into the slag as sulfur ion. Consequently, the sulfur content in the metal pool reduces. The desulfurization rate at the metal pool-slag interface is positive. On the contrary, the electrons flow from the slag to the metal at the metal droplet-slag interface. The electrons would separate themselves from sulfur ions in the slag, and come back to the metal as sulfur atom resulting in the increase of the sulfur concentration. Thus, the desulfurization rate at the metal droplet-slag interface is negative.

Figure 8 shows the effect of current on the volume-average temperature of the slag. Due to more Joule heating, the slag becomes hotter with the increasing of the current. The desulfurization caused by the slag treatment would be promoted by the stronger current because of the higher temperature. And according to Eq. (12), the value of the transfer rate induced by DC also becomes larger. The overall transfer rate at the metal droplet-slag interface therefore is decided by the competition of these two transfer rates. When the negative transfer rate outweighs the positive one, the sulfur content in the metal droplet would rise other than drop. On the other hand, the overall transfer rate at the metal pool-slag interface is improved by the higher current, because the two transfer rates at this interface are all positive.

Figure 9 illustrates the effect of the current on the sulfur concentration at point 1. It is clear that the sulfur content at point 1 in the slag increases during the desulfurization process. Nevertheless, the five evolutions of the sulfur content at the later stage tell a different story due to the influence of the current. At this period, the concentration at point 1 under 1 500 A current is higher than that under 1 200 A current, while the concentration gradually decreases within the current range from 1 800 A to 2 400 A. It is the result of the competition between the two transfer rates induced by the slag treatment and DC, respectively. The negative transfer rate induced by the DC would exceed the positive transfer rate caused by the slag treatment with the increasing of the current, and the overall transfer rate at the metal droplet-slag interface changes from positive to negative, which reduces the desulfurization effect.
In addition, the calculated mass percent of sulfur reasonably matches with the measured one. It can be noted that the measured value is lower than the simulated value at the later period, because sulfur in the slag would be oxidized by the air in practice, and then escape into the atmosphere as sulfur dioxide. The present model however did not consider this process.

**Figure 10** displays the simulated removal ratio of sulfur, which is defined as the ratio of the total sulfur content in the slag to that in the original metal. The largest removal ratio, around 88%, is obtained when the current is 1500 A. The removal ratio then decreases from 88% to 65%, while the current changes from 1500 A to 2400 A.
Fig. 10. Effect of the current on the removal ratio of sulfur.

6. Conclusions

A transient 3D mathematical model has been established to study the effect of the current on the desulfurization behavior in the DC ESR process. The solutions of the mass, momentum, energy, and species conservation equations were simultaneously solved by the finite volume method. The movement of the metal droplet was described by the VOF approach. A dynamic module was introduced to represent the desulfurization mechanism including the effects of the slag composition and the current. Three experiments have been conducted to validate the model. The comparison between the measured and simulated data indicates that the model can predict the desulfurization with acceptable accuracy. A positive transfer rate is induced by the slag treatment and a negative one is created by DC at the metal droplet-slag interface. The volume-average temperature of the slag increases from 1 940 K to 2 019 K, while the current ranges from 1 200 A to 2 400 A. The desulfurization caused by the slag treatment is promoted by the stronger current because of the higher temperature. The value of the negative transfer rate induced by DC also becomes larger with the increasing of the current. The overall transfer rate at this interface is decided by the competition of these two transfer rates. The removal ratio of sulfur increases from 82% to 88% when the current changes from 1 200 A to 1 500 A, and then drops to 65% if the current continuously increase to 2 400 A.

Acknowledgements

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Nomenclature

\[ A: \text{ specific surface area for reaction (m}^{-1}\text{)} \]
\[ a_{\text{Al}}: \text{ activity of aluminum in the metal} \]
\[ a_{\text{Al}_2\text{O}_3}: \text{ activity of alumina in the slag} \]
\[ a_{\text{O}}: \text{ activity of oxygen in the metal} \]
\[ C_s: \text{ sulfide capacity of the slag} \]
\[ D: \text{ mass percent of sulfur (%)} \]
\[ \varepsilon_{ij}: \text{ interaction coefficient of the element } j \text{ with respect to the element } i \]
\[ F: \text{ Faraday law constant (C/mol)} \]
\[ f_i: \text{ activity coefficient of the element } i \text{ in the metal} \]
\[ J: \text{ current density (A/m}^2\text{)} \]
\[ K: \text{ reaction equilibrium constant} \]
\[ k_{sm}: \text{ mass transfer coefficient of sulfur in the metal (m/s)} \]
\[ k_{ss}: \text{ mass transfer coefficient of sulfur in the slag (m/s)} \]
\[ L_s: \text{ partition ratio of sulfur} \]
\[ S_i: \text{ source term in Eq. (1)} \]
\[ T: \text{ temperature (K)} \]
\[ \dot{V}: \text{ velocity (m/s)} \]
\[ w[i]: \text{ mass percent of the element in the metal and in the slag (}) \]

Greek symbols

\[ \alpha: \text{ volume fraction of each phase} \]
\[ \bar{\rho}: \text{ density of mixture phase (kg/m}^3\text{)} \]
\[ \Lambda: \text{ optical basicity of the slag} \]

REFERENCES