Effect of Traveling Magnetic Field on Flow, Mixing, Decarburization and Inclusion Removal during RH Refining Process

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In order to improve productivity during RH refining, the traveling magnetic field was imposed around the snorkels. The numerical method was employed to investigate the flow, mixing, decarburization and inclusion removal in RH degasser. Numerical results showed that the predicted results agree well with the experimental data. With the increasing current, the circulation flow rate increases and the mixing time decreases. If the current frequency lies in the range of 10–30 Hz, with the increasing current frequency, the circulation flow rate increases while the mixing time decreases. If the current frequency lies in the range of 30–60 Hz, with the increasing current frequency, the circulation flow rate decreases while the mixing time increases. In order to increase circulation flow rate and shorten mixing time, the most effective measure is to apply the traveling magnetic field around the up snorkel, and the second choice is to apply the traveling magnetic field around the down snorkel if the gas flow rate is smaller than the saturation value. Applying the traveling magnetic field can accelerate the decarburization rate during the process, but can not decrease the final carbon mass concentration. For inclusion removal, the most effective measure is to apply the traveling magnetic field around the up snorkel and down snorkel, and to apply the traveling magnetic field around the up snorkel has the minor effect. Furthermore, the application of traveling magnetic field can decrease the maximum inclusion characteristic radius and the related peak value time.

KEY WORDS: numerical simulation; RH; traveling magnetic field; circulation flow rate; mixing time; decarburization; inclusion removal.

1. Introduction

During the past several decades, as one of the main metallurgical reactors to produce ultra-low carbon steel, Rheinsahl–Heraeus (RH) degasser plays a more and more important role in the refining process for degassing, mixing, and decarburization before continuous casting process.1–3) Furthermore, RH degasser is also an important metallurgical reactor for inclusion removal after deoxidization.4) During the industrial production, the steel temperature often drops inevitably, so the aluminum addition or the post combustion of carbon monoxide with oxygen is often employed to raise the temperature of liquid steel.5,6) However, the excessive oxygen from top-blowing lance has to be removed by deoxidization which would prolong the RH refining time.4,7) Therefore, the decarburization, degassing, alloying and inclusion removal should be enhanced by increasing the circulation flow rate and shortening the mixing time.

In order to improve the RH refining productivity, lots of studies concerning the circulation flow rate have been conducted.8–19) Some researches showed that the circulation flow rate is mainly determined by the vacuum degree and the lifting gas flow rate,8–12) and it is difficult to increase the circulation flow rate after reaching its saturation value.8,9)

Meanwhile, several measures have also been taken to increase the circulation flow rate and shorten mixing time, such as increasing the diameter of the up snorkel and the down snorkel,13) using the oval-shape-snorkels,10) replacing one up snorkel and one down snorkel by three up snorkels and one down snorkel,14) two up snorkels and one down snorkel or one up snorkel and two down snorkels,12) applying rotating magnetic field around the up snorkel,15) blowing additional argon gas, (e.g. blowing argon gas through vacuum chamber bottom16) and ladle bottom17,18) and so on.

On the other hand, based on the mechanism that the liquid steel can be accelerated by electromagnetic force, Zhang et al.19) proposed that the application of the traveling magnetic field around the up snorkel or the down snorkel can increase the circulation flow rate in RH degasser. As shown in Fig. 1, the traveling magnetic field is imposed around the up snorkel or the down snorkel. The origin of the rectangular coordinate system is located at the center of the up snorkel. The windings were connected to the three-phase alternating current to generate the traveling magnetic field. By changing the phase sequence of the exciting current,20) the axial electromagnetic force can direct upward or downward. Thus, the liquid steel can be accelerated both in up snorkel and down snorkel.
The purpose of the present study is to promote the RH refining productivity by applying the traveling magnetic field around the up snorkel or the down snorkel. And the numerical simulation method has been employed to understand the two-phase flow under the traveling magnetic field in RH degasser. Moreover, the decarburization and inclusion removal have also been investigated.

2. Mathematical Model

The developed mathematical model consists of the following four parts: traveling magnetic field, gas-liquid flow field, decarburization and inclusion removal in RH degasser on the base of the following assumptions.

Assumptions concerning traveling magnetic field

1. Since the exciting current is the low frequency sinusoidal current, the quasi-static condition is satisfied and the displacement current can be neglected.
2. The liquid steel, windings, iron core and air are the isotropic materials.
3. The effect of electromagnetic field on gas bubbles can be neglected.

Assumptions concerning gas-liquid flow

4. The fluids in both the gas and liquid phases are Newtonian, viscous and incompressible, and the fluid flow is at the steady state.
5. The effect of top slag on fluid flow is neglected and the free surface is flat.
6. The gas bubbles are spherical and the interactions among bubbles are not considered.
7. The fluid flow in RH degasser is an isothermal process.

Assumptions concerning inclusion removal process

8. The effect of inclusion movement on fluid flow in RH degasser is neglected.
9. The inclusions are spherical and each inclusion moves independently before the collision occurs.
10. The effect of bubbles on inclusion removal can be neglected because there is no top slag in vacuum chamber.
11. The fractional inclusion number density has an exponential relationship with the inclusion radius and can be expressed as: \( f(r) = Ae^{-B(r)} \). So the inclusion number density, the inclusion volume concentration and the characteristic inclusion radius can be expressed as:

\[
N^* = \int_0^\infty f(r) dr = \frac{A}{B}, \quad C^* = \int_0^\infty \frac{4}{3} \pi r^3 f(r) dr = 8\pi \frac{A}{B^3}, \quad \text{and} \quad r^* = \sqrt[6]{6}/B \text{ respectively.} \]

Assumptions concerning decarburization process

12. The contents of carbon and oxygen at the gas-liquid interface are in equilibrium with CO partial pressure in gas phase.
13. The decarburization rate is controlled by the mass transfer of carbon and oxygen in liquid steel.
14. The decarburization in RH degasser takes place at the free surface of vacuum chamber, the inner site of liquid steel and the bubble surface of gas-liquid plume.

2.1. Governing Equations

2.1.1. Traveling Magnetic Field

Since the magnetic Reynolds number is much smaller than 1, the effect of fluid flow on electromagnetic field can be neglected. Consequently, the current \( \mathbf{j} \) and the magnetic flux density \( \mathbf{B} \) are governed by the Maxwell equations as follows,

\[
\nabla \times \mathbf{H} = \mathbf{j} \quad \text{.................................. (1)}
\]

\[
\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad \text{.................................. (2)}
\]

\[
\nabla \cdot \mathbf{B} = 0 \quad \text{.................................. (3)}
\]

\[
\mathbf{B} = \mu_0 \mathbf{H} \quad \text{.................................. (4)}
\]

\[
\mathbf{j} = \sigma_\mathbf{E} \quad \text{.................................. (5)}
\]

where \( \mathbf{H} \) is the magnetic density, A/m; \( \mathbf{E} \) is the electric field intensity, V/m; \( \mu_0 \) is the magnetic permeability, H/m; \( \sigma_\mathbf{E} \) is the electric conductivity, S/m. Moreover, the actual electromagnetic force which accelerates the fluid flow can be expressed as a time-averaging form,

\[
\mathbf{F}_{\text{em}} = \frac{1}{2} \text{Re}\left( \mathbf{j} \times \mathbf{B}^* \right) \quad \text{.................................. (6)}
\]

where \( \mathbf{B}^* \) is the conjugate complex number of \( \mathbf{B} \). Moreover, the calculated time-averaging electromagnetic force vector is incorporated into the gas-liquid two phase flow model as the source term of the momentum conservation equation.

2.1.2. Flow Field and Mixing Behavior in RH Degasser

In order to simulate the gas-liquid flow in RH degasser, the model developed and validated in the previous paper was employed in the present work.\(^9\) Based on the above assumptions (4)-(7), the following governing equations are solved in the model,\(^9\)

- the continuity and momentum equations for the mixture of gas and liquid phases
- the volume fraction equation for the dispersed phase
- the \( k-e \) two equations

The tracer transport equation are solved to obtain the variation of dimensionless tracer concentration with time. Furthermore, the mixing time is defined as the time to reach a 95% level of homogeneity, i.e., all the monitoring points in
RH degasser are within ±5% of the homogeneous concentration value.9)

2.1.3. Inclusion Removal in RH Degasser

The transport equations which describe collision and aggregation among inclusions can be expressed as follows:24,25)

\[
\frac{\partial}{\partial t} \left( \rho_l N^d \right) + \nabla \cdot \left( \rho_l N^d \mathbf{v}_l \right) = \nabla \cdot \left( D_{eff} \nabla N^d \right) + S_{N^d}
\]

\[\nabla \cdot \left( \rho_l \mathbf{v} \right) = \nabla \cdot \left( D_{eff} \nabla \mathbf{v} \right)
\]

Here, \( \rho_l \) and \( \rho_p \) are the density of liquid steel and inclusion, kg/m³; \( \mathbf{v}_l \) is the kinematic viscosity of liquid steel, m²/s; \( g \) is the gravitational acceleration, m/s²; \( D_{eff} \) is the effective diffusion coefficient, m²/s. Moreover, the source term \( S_{N^d} \) accounts for the effect of the coalescence among inclusions on the inclusion number density. Because the effect of turbulent collisions and Stokes collisions on the inclusion growth is remarkable while the effect of Brownian collisions is negligible, both the turbulent collisions and Stokes collisions have been taken into account in the present work and the collision rate among inclusions with radii \( r_i \) and \( r_j \) is given by:25)

\[
S_{N^d} = -N^d \cdot r^3 \left[ 1.9 \left( \frac{5 \left( 6 \pi \rho_l \nu_l^2 \left( 4 \varepsilon / 15 \pi \nu_l \right)^{0.5} \right)}{A^*} \right) \right]^{0.242} \left( \frac{\pi \varepsilon}{\nu_l} \right) + \frac{10 \Delta \rho \pi r^4}{9 \sqrt{6} \rho_l \nu_l}
\]

Here, the value of Hamaker constant \( A^* \) is 0.48×10⁻²⁰ J for alumina inclusion;26) \( r \) is the initial size of the monomer particle, m.

At the top slag, it is assumed that 80% of the inclusions reaching top slag are removed while the remaining 20% of the inclusions are entrained into the liquid steel.24 The inclusion adhesion to the refractory wall can be treated as the mass diffusion of boundary layer.24,26 Moreover, at the ladle bottom, the reverse effect of inclusion flotation velocity on the inclusion adhesion has also been taken into account. Thus, the boundary fluxes for inclusion number density and concentration are listed in Table 1.25)

2.1.4. Decarburization in RH Degasser

The governing equation for calculating the concentration distribution of carbon and oxygen can be represented as,1)

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = \nabla \cdot (\rho \mathbf{v} \mathbf{v}) + \rho \mathbf{g} + \nabla \cdot (\rho d \nabla \mathbf{v}) + \nabla \cdot (\rho \mathbf{v} \mathbf{v} \mathbf{v}) + \rho \nabla \cdot (\nabla \rho) + S_{\rho}
\]

\[
\frac{\partial C}{\partial t} + \nabla \cdot (C \mathbf{v}) = \nabla \cdot (C \mathbf{v} \mathbf{v}) + \rho \mathbf{g} + \nabla \cdot (C \mathbf{v} \mathbf{v}) + \nabla \cdot (C \mathbf{v} \mathbf{v} \mathbf{v}) + \rho \nabla \cdot (\nabla C) + S_{C}
\]

Table 1. Boundary Fluxes for inclusion number density and concentration.

| Boundary     | \( N^* \) | \( C^* \) |
|--------------|------------|------------|
| Top slag     | \( \frac{\partial N^*}{\partial t} - D_{eff} \nabla N^* \) | \( \frac{\partial C^*}{\partial t} - D_{eff} \nabla C^* \) |
| Sidewall     | \[ -u_N^d \sin \theta + \frac{\tau_{NJ} \mathbf{v}_N}{100 \nu_l} \] | \[ -u_N^d \sin \theta + \frac{4 \pi \nu_l N^d r^4}{75 \nu_l} \] |
| Bottom       | \[ -u_N^d \sin \theta + \frac{\tau_{NJ} \mathbf{v}_N}{100 \nu_l} \] | \[ -u_N^d \sin \theta + \frac{4 \pi \nu_l N^d r^4}{75 \nu_l} \] |

Here, \( \theta \) is the include angle between wall face and vertical direction, and \( \tau_{NJ} \) is the wall shear stress.

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = \nabla \cdot \left( \frac{\mu_{eff}}{Sc} \nabla \rho \right) + S_{\rho} \quad \text{(10)}
\]

where \( \rho \) represents the mass concentration of carbon and oxygen; \( \mu_{eff} \) is the effective viscosity, Pa·s; \( Sc \) is the turbulent Schmit number; \( S_{\rho} \) is the source or sink of carbon and oxygen and can be obtained as follows,

\[
S_{\rho} = \frac{dw^1}{dt} + \frac{dw^2}{dt} + \frac{dw^3}{dt} \quad \text{(11)}
\]

where \( \frac{dw^1}{dt} \), \( \frac{dw^2}{dt} \) and \( \frac{dw^3}{dt} \) are the decarburization rates at three different sites. The decarburization rate at the free surface of the vacuum chamber can be expressed as,25)

\[
\frac{dw^1}{dt} = \frac{M_a}{1000} \frac{2.1 A_c}{V} \min \left[ \frac{k_{c,l}}{M_c} \left( w_c - w_c^* \right), \frac{1000}{M_c} \left( w_c - w_c^* \right) \right] \quad \text{(12)}
\]

where \( M_a \) is the molar mass of carbon and oxygen, g/mol; \( w_c^* \) and \( w_c^* \) are the mass concentration of carbon and oxygen at the reaction surface; \( A_c \) is the cross section area of vacuum chamber, m²; \( k_{c,l} \) and \( k_{o,l} \) are the mass transfer coefficient of dissolved carbon and oxygen in liquid steel, m/s.

The decarburization rate at the surface of argon bubbles can be expressed as,

\[
\frac{dw^1}{dt} = \frac{M_a}{1000} \frac{6a_A d_b}{\pi d_b^3} \min \left[ \frac{k_{c,b}}{M_c} \left( w_c - w_c^* \right), \frac{1000}{M_c} \left( w_c - w_c^* \right) \right] \quad \text{(13)}
\]

where \( A_b \) is the surface area of argon bubbles, m²; \( d_b \) is the bubble diameter, m; \( k_{c,b} \) is the mass transfer coefficient of dissolved carbon or oxygen from liquid steel to the bubble surface, m/s; \( D_b \) is the diffusion coefficient of dissolved carbon or oxygen, m²/s; \( v_b \) is the bubble flotation velocity, m/s.

The decarburization in the inner site of the vacuum chamber occurs when the equilibrium CO pressure exceeds the hydrostatic pressure. Thus, CO bubbles can nucleate when the equilibrium CO pressure is great enough. Such a mech-
anism can be expressed as, 29)
\[
\frac{d w_0^3}{dt} = K_0 h (K_{CO} w_C w_O - P_v) \quad \ldots \ldots \ldots (14)
\]
where \( K_0 \) is a constant with value of \( 2 \times 10^{-6} \text{Pa}^{-1} \text{s}^{-1} \text{m}^{-1} \); \( K_{CO} \) is the decarburization reaction equilibrium constant; \( P_v \) is the pressure in vacuum chamber, Pa; \( h \) is the distance from the free surface in vacuum chamber, m.

2.2. Boundary Conditions and Parameters
For all nodes at the refractory walls in RH degasser, wall function method was applied, and the normal gradients of pressure and gas volume fraction were also set to zero. For the free surfaces in ladle and vacuum chamber, the symmetry boundary condition was imposed. Furthermore, the gas bubbles reaching the free surface were assumed to escape at flotation velocity. The tracer was added at the center of the free surface in vacuum chamber. For the computation of magnetic field, the magnetic flux is set to be parallel to the surrounding surface of air. The relative magnetic permeability of air, liquid steel and windings are set to be 1, while the relative magnetic permeability of iron core is set to be 1 000. The conductivity of windings and liquid steel are 1.78\( \times 10^7 \) S/m and 7.14\( \times 10^5 \) S/m respectively. The density of argon gas (STP) and liquid steel are 1.783 kg/m\(^3\) and 7020 kg/m\(^3\) respectively. And the viscosity of liquid steel is 0.0062 Pa·s.9) Moreover, the dimensions of RH degasser are shown in Table 2.

2.3. Solution Method
The whole computation process can be divided into three parts. (1) The traveling magnetic field was obtained by finite element method. The commercial finite element software package, ANSYS, was employed to calculate the external electromagnetic field produced by the electromagnetic equipments. (2) The steady gas-liquid flow under traveling magnetic field was calculated by adding the electromagnetic force to momentum conservation equation for liquid steel as the source term. The computational fluid dynamics package, CFX, was employed to obtain the flow field. (3) The unsteady conservation equations for carbon concentration, oxygen concentration, inclusion number density and volume concentration were also solved by CFX. The finite volume method was used to solve these partial differential equations. The grids of RH degasser consisted of about 900 000 control volumes and the grid sensitivity experiments were conducted. In order to get more detailed information in two-phase domain, a densely packed grid system was applied in the snorkels and vacuum chamber. The convergence criteria is that the value of the root mean square normalized residual for variables was less than 1\( \times 10^{-3} \) and the global imbalance, which means the ratios of the difference between the total input mass flux and the total output mass flux to the total input gas mass flux was less than 0.1%.

3. Results and Discussion
3.1. Model Validation
The CT-3 Teslameter has been employed to measure the magnetic induction intensity 2 cm away from the traveling magnetic field generator. Figure 2 shows that the predicted magnetic induction intensity at different locations is in good agreement with the experimental data.33) As shown in Fig. 3, the calculated circulation flow rate is also in good agreement with the experimental data.30) And with the increasing

| Table 2. Dimensions of RH system and calculation conditions. |
|---------------------------------------------------------------|
| Parameters value                                              |
| Up diameter of ladle, mm                                       | 3 190 |
| Down diameter of ladle, mm                                     | 2 860 |
| Diameter of snorkels, mm                                       | 480  |
| Diameter of vacuum chamber, mm                                 | 1 870 |
| Immersion depth of snorkels, mm                               | 480  |
| Exciting current frequency, Hz                                 | 10–60 |
| Exciting current, A                                            | 25–200|
| Coil turns                                                    | 72    |
| Height of magnetic field generator, mm                        | 800   |

Fig. 2. Comparison of calculated magnetic induction intensities with experimental results.

Fig. 3. Comparison of calculated circulation flow rates with experimental results.
gas flow rate, the circulation flow rate increases and reaches a critical maximum value, then decreases. Moreover, in our previous work, the model employed has also been validated by comparing the calculated mixing time, gas penetration depth, velocity and dimensionless tracer concentration with the experimental data.

With respect to the metallurgical phenomena, the measured results about the decarburization and the inclusion removal were employed to verify the numerical model. Figure 4 shows that the calculated carbon removal rate is consistent with the experimental data. Besides, Table 3 also shows that the predicted inclusion mass fraction is also in good agreement with the experimental value. The difference between the numerical results and the experimental data comes from the affection of the sampling position in the experiment.

3.2. Effect of Imposing Position of Magnetic Field

Figures 5 and 6 show that by using 200 A of exciting current and 10 Hz of current frequency, the circulation flow rate is up 16–40 percent, and the mixing time falls 13–17 percent by imposing the traveling magnetic field around the up snorkel. On the other hand, the circulation flow rate is up 16–35 percent, and the mixing time can be decreased by 9–13 percent by imposing the traveling magnetic field around the down snorkel. Furthermore, the circulation flow rate in RH degasser with traveling magnetic field imposed around the up snorkel is greater than that with traveling magnetic field imposed around the down snorkel if the lifting gas flow rate is less than 1600 NL/min, but they are almost the same if the lifting gas flow rate is greater than 1600 NL/min. The effect of centripetal electromagnetic force is the key factor leading to this interesting phenomenon. When the traveling magnetic field is imposed around the up snorkel, the liquid steel can be moved to the center by centripetal electromagnetic force, so more gas bubbles can be transported to the center and more liquid steel can be accelerated by gas bubbles. However, the gas volume at up snorkel center would become saturated with the increasing lifting gas flow rate. Thus, such a difference disappears if the gas flow rate is greater than 1600 NL/min.

Moreover, Figs. 5 and 6 also show that the circulation flow rate is up 30–66 percent, and the mixing time falls 18–26 percent by imposing the traveling magnetic field around the up snorkel and down snorkels simultaneously. For example, on the condition of 1000 NL/min of lifting gas flow rate, when the traveling magnetic field was imposed on the up snorkel and down snorkel simultaneously, the circulation flow rate can rise from 77.1 t/min to 107.1 t/min and the mixing time can fall from 123.9 s to 96.5 s.

3.3. Effect of Exciting Current Parameters

Figure 7 shows that horizontal and vertical components of electromagnetic force increase with the increasing exciting current. The reason is that both the magnetic induction intensity and the induced eddy current increase with the increasing exciting current. Moreover, the electromagnetic force increases with the increasing exciting current. Moreover,
Fig. 7 also shows that the vertical component of electromagnetic force is much greater than the horizontal component, so the liquid steel in up snorkel or down snorkel can be accelerated by the electromagnetic force effectively.

Figure 8 shows that on the condition of 10 Hz of exciting current frequency, when the current rises from 100 A to 600 A, the circulation flow rate rises from 81.5 t/min to 158.5 t/min, and the mixing time falls from 120.1 s to 60.2 s. The reason is that the exciting current has the more profound effect on the axial component of electromagnetic force than that on the horizontal component of electromagnetic force. So the liquid steel flow can be accelerated and the circulation flow rate increases. Moreover, the axial electromagnetic force increases with the increasing exciting current. In this way, with the increasing exciting current, the circulation flow rate increases and the mixing time decreases. Therefore, the RH refining efficiency can be improved by increasing the exciting current. However, great joule heat produced by large exciting current will destroy the traveling magnetic field equipment.

Meanwhile, Fig. 9 shows the effect of exciting current frequency on the horizontal and vertical components of electromagnetic force. The induced eddy current in liquid steel is mainly at the horizontal plane and increases with the increasing exciting current frequency. The magnetic induction intensity almost keeps unchanged with the variation of exciting current frequency. Moreover, the vertical component of magnetic induction intensity is much larger than the horizontal component. Therefore, with the increasing exciting current frequency, the horizontal component of electromagnetic force increases while the vertical component
almost keeps unchanged if the current frequency is greater than 30 Hz.

As shown in Fig. 10, on the condition of 200 A of exciting current, when the current frequency rises from 10 Hz to 30 Hz, the circulation flow rate rises from 93.9 t/min to 118.3 t/min, and the mixing time falls from 104.7 s to 87.7 s. Then the circulation flow rate falls to 112.2 t/min and the mixing time is up to 91.8 s when the current frequency is equal to 60 Hz. Such phenomena are related to the bubbles’ behavior. It is difficult for the gas bubbles to reach the up snorkel center in traditional RH degasser. But with the help of horizontal electromagnetic force, the bubbles have more chances to reach the up snorkel center. Moreover, the gas bubbles at the up snorkel center can accelerate liquid steel more effectively than that near the sidewall of up snorkel. On the other hand, with the increasing exciting current frequency, the horizontal electromagnetic force increases while the vertical electromagnetic force can hardly be affected. So the circulation flow rate increases with the increasing current frequency if the current frequency is smaller than 30 Hz. However, the gas volume becomes saturated when the current frequency is up to 30 Hz. Thus, the circulation flow rate decreases and the mixing time increases if the exciting current frequency is greater than 30 Hz.

3.4. Effect of Traveling Magnetic Field on Decarburization and Inclusion Removal

In order to investigate the effect of the traveling magnetic field on the decarburization and the inclusion removal during RH vacuum refining process, the related numerical simulation were performed on the condition of lifting gas flow rate of 1 000 NL/min, exciting current of 300 A, and current frequency of 10 Hz. And the traveling magnetic field was

![Fig. 10](image-url). Effect of current frequency on circulation flow rate and mixing time (Lifting gas flow rate=1 000 NL/min).

![Fig. 11](image-url). Effect of different positions of magnetic field on decarburization in RH degasser (Lifting gas flow rate=1 000 NL/min).

![Fig. 12](image-url). Predicted isometric contour of carbon concentration after 500 seconds. (a) No magnetic field (b) Magnetic field imposed around up snorkel (c) Magnetic field imposed around up snorkel and down snorkel.
imposed around up snorkel, up snorkel and down snorkel, respectively.

Figure 11 shows that the decarburization rate in RH degasser with traveling magnetic field imposed around up snorkel is greater than that without magnetic field and the decarburization rate with traveling magnetic field imposed around up snorkel and down snorkel is greater than that with traveling magnetic field imposed around up snorkel. Several reasons lead to this phenomenon. Firstly, the turbulent flow of liquid steel in up snorkel and vacuum chamber becomes more drastic in RH degasser with traveling magnetic field imposed around up snorkel, so the mass transfer coefficient in up snorkel and vacuum chamber increases. Secondly, the circulation flow rate in RH degasser with traveling magnetic field imposed around up snorkel and down snorkel is larger than that in RH degasser with traveling magnetic field imposed around up snorkel. At last, the mixing time decreases with the increasing circulation flow rate, so better mixing effect is in favor of decarburization.

Figure 12 shows that the carbon mass concentration in RH degasser with traveling magnetic field imposed around up snorkel is much smaller than that without magnetic field. And the carbon mass concentration with traveling magnetic field imposed around up snorkel and down snorkel is much smaller than that with traveling magnetic field imposed around up snorkel. However, the final carbon mass concentration is determined by the pressure in vacuum chamber. Thus, the traveling magnetic field can accelerate the decarburization rate during the process, but can not decrease the target carbon mass concentration.

Figure 13 shows that the inclusion number density and concentration decrease most quickly in the RH degasser with traveling magnetic field imposed around up snorkel and down snorkel, while the inclusion number density and concentration decrease slowly in the traditional RH degasser. The reasons are as follows. Firstly, the turbulent energy dissipation rate is very great when the traveling magnetic field was imposed around up snorkel or down snorkel and greater turbulent energy dissipation rate can promote the collision and coalescence among inclusions more effectively. Secondly, larger inclusions can be removed by the adhesion to the top slag because of the greater flotation velocity. In this way, the inclusion removal rate in RH degasser with traveling magnetic field imposed around up snorkel is greater than that without magnetic field. And the inclusion removal rate in RH degasser with traveling magnetic field imposed around up snorkel and down snorkel is greater than that with traveling magnetic field imposed around up snorkel.

Fig. 13. Evolution of inclusion characteristic parameters during inclusion removal process (Lifting gas flow rate=1 000 NL/min).

Fig. 14. Predicted isometric contour of inclusion number density after 200 seconds. (a) No magnetic field (b) Magnetic field imposed around up snorkel (c) Magnetic field imposed around up snorkel and down snorkel.
imposed around up snorkel and down snorkel is greater than that in RH degasser with traveling magnetic field imposed around up snorkel.

Figure 13 also shows that in the traditional RH degasser, the inclusion characteristic size increases at initial stage, and then decreases. Collision and aggregation among inclusions lead to such interesting phenomena. At the initial stage, the number of new bigger inclusions after aggregation is much more than that of the removed bigger inclusions, so the inclusion characteristic size increases continuously. Once the number of big inclusions after aggregation is less than that of big inclusions removed, the inclusion characteristic size decreases.

Furthermore, the maximum inclusion characteristic radius \(r_{\text{max}}\) and the related peak value time \(t_{pv}\) (the time corresponding to the maximum of inclusion characteristic radius) can be observed in Fig. 13. In the case of no magnetic field, \(r_{\text{max}} = 3.85 \mu m, t_{pv} = 460\) s. If the traveling magnetic field is imposed around the up snorkel, \(r_{\text{max}} = 3.97 \mu m, t_{pv} = 705\) s. If the traveling magnetic field is imposed around the up snorkel and down snorkel, \(r_{\text{max}} = 4.29 \mu m, t_{pv} = 884\) s. So the application of traveling magnetic field can decrease the inclusion size and the peak value time effectively.

Figure 14 shows that the inclusion number density in RH degasser with traveling magnetic field imposed around up snorkel is much smaller than that without magnetic field. And the inclusion number density in RH degasser with traveling magnetic field imposed around up snorkel and down snorkel is much smaller than that with traveling magnetic field imposed around up snorkel.

4. Conclusions

The numerical method was employed to investigate the two-phase flow field, mixing time, decarburization and inclusion removal on the condition of traveling magnetic field imposed on the snorkels in RH degasser. And the effect of different exciting current parameters on the RH refining process was also discussed. For RH imposed by traveling magnetic field, the following conclusions can be obtained.

(1) With the increasing current, the circulation flow rate increases and the mixing time decreases.

(2) If the current frequency lies in the range of 10–30 Hz, with the increasing current frequency, the circulation flow rate increases while the mixing time decreases. But if the current frequency lies in the range of 30–60 Hz, with the increasing current frequency, the circulation flow rate decreases while the mixing time increases.

(3) In order to increase circulation flow rate and shorten mixing time, the first measure is to apply the traveling magnetic field around the up snorkel, and the second is to apply the traveling magnetic field around the down snorkel if the gas flow rate is smaller than the saturation value. However, such a difference disappears if the gas flow rate is greater than the saturation value.

(4) For decarburization, by imposing the traveling magnetic field around up snorkel or down snorkel can accelerate the decarburization rate during the process, but can not decrease the target carbon mass concentration.

(5) For inclusion removal, the most effective measure is to apply the traveling magnetic field around the up snorkel and down snorkel, and to apply the traveling magnetic field only around the up snorkel has the minor effect.

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