Effect of Side-blowing Arrangement on Flow Field and Vanadium Extraction Rate in Converter Steelmaking Process

Fuhai LIU,1,2) Dongbai SUN,3) Rong ZHU,2)* Kai DONG2) and Ruiguo BAI3)

1) National Center for Materials Service Safety, University of Science and Technology Beijing, Beijing, 100083 China.
2) Beijing Key Laboratory of Research Center of Special Melting and Preparation of High-end Metal Materials, University of Science and Technology Beijing, Beijing, 100083 China.
3) Chengde Iron and Steel Company, Chengde, Hebei, 067002 China.

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To improve the vanadium extraction rate, the iron ore powder was used to be injected into the molten bath by side-blowing. Both simulation numerical and water experiment model for analyzing the behaviors of molten bath flow field had been developed to investigate the mixing time, velocity profile and dead-zone volume of molten steel under various injection arrangements and gas flow rates. The result showed that the mixing time would reduce, with increasing the distance between side-blowing nozzle and molten bath surface. Moreover, although the kinetic energy would be removed by the mutual influenced between bottom-blow bubbles and the side-blowing jet at a certain content, the stirring effect of molten bath is still improved by the side-blowing jet. Based on the result of simulation, an injection arrangement was used in the 150 t vanadium extraction converter. Based on the results, the vanadium content of semi-steel and T. Fe in the slag with side-blowing arrangement is 0.033% and 34.1%, respectively. And the vanadium content of semi-steel and T. Fe in the slag with side-blowing arrangement is 0.044% and 32.1%, respectively.

KEY WORDS: side-blowing; powder injection; vanadium extraction; simulation.

1. Introduction

As a valued element, the vanadium could improve the plasticity and corrosion resistant of steel. For the traditional vanadium extraction method, the vanadium would be oxidized to V2O5 and transmitted into liquid slag in converter steelmaking process.1–3) However, there would be an optional oxidation process between vanadium and carbon. Therefore, both the thermodynamic and dynamic conditions should be analyzed to suppress the carbon–oxygen reaction for increasing the vanadium extraction rate. Based on the literatures,4–7) with an appropriate FeO content in liquid slag, lowering the smelting temperature and improving the stirring effect could achieve bigger vanadium extraction rate. At present, optimizing the stirring effect of molten bath is a proper method to enhance the vanadium extraction rate, and the smelting temperature is controlled by adding the slag material during steelmaking process.

Both the oxygen lance structure and bottom-blowing arrangement have been researched to improve the dynamic condition of molten bath for a long time, and the powder injection technology is also carried out in recent years. Kruskopf8) researched the effects of bottom-blowing structure nozzle and flow rate on the flow field of molten bath by numerical simulation with the scrap melting and chemical reaction model. Higuchi and Tago9) proposed that twisted nozzle oxygen lance could suppress the spitting rate of liquid slag, and increase the stirring effect of molten bath in steelmaking process. Tang and Wang et al.10) adopted the water experiment to analyze the powder injection effect in converter steelmaking process, and shown the optimum operation was lance height being 1 550 mm, powder size being 1–5 mm and bottom blowing rate being 450 Nm3·h−1.

Yamanoglu and Guthrie et al.11) found that the diffusion effect of powder would be improved with increasing carrier gas flow rate, and the appropriate solid-gas ratio could enhance the impaction area and stirring effect.

When the slag material with the size of powder is injected into molten steel by the side-blowing, the reactions in molten bath could be accelerated, compared to conventional injection method. At the same time, the powder with large kinetic energy could also improve the stirring effect of molten bath, during powder injection process. As a result, both metallurgical and operation benefits could be achieved by the powder injection technology, as shown in the literatures. Hence, Chengde Iron and Steel Company wants to apply the powder injection technology in a 150 t vanadium extraction converter. At present, many research achievements have been obtained mainly on the studies of lime-powder injection method, but the lime is banned in the vanadium extraction process. Since, CaO addition would decrease the level
of vanadium content in slag, leading to disadvantage for economic recovery. Hence, it was necessary to carry out the research of water experiment and numerical simulation for the powder injection method before industrial application.

In the present study, behavior of flow field and stirring ability of molten bath with various kinds of powder injection arrangement had been analyzed, and the results would be compared with conventional vanadium extraction process. Mixing time, average velocity and dead-zone volume were measured by water experiment and numerical simulation. Based on the results, an appropriate arrangement was applied in a 150 t vanadium extraction converter to analyze smelting time, \( V_{2}O_{5} \) and Fe content in slag.

2. Water Experiment Model

2.1. Experimental Principle

Based on the similarity of kinetics and geometry, the water experiment model of converter with one powder injection nozzle has been built. The effect of the temperature on the dynamic pressure of the jet is relatively small, according to the research.\(^{12-14}\) Therefore, the temperature effects were not considered in this paper. As shown in Eq. (1), the modified Froude number was adopted to make the model dynamically similar to the 150 t vanadium extraction converter, and the inertial force and gravity was took into account.

\[
Fr' = Fr'_{1}, \text{that was } \frac{u_{1}^{2}}{gd_{1}} \times \frac{\rho_{s}}{\rho_{g}} = \frac{u_{1}^{2}}{gd_{1}'} \times \frac{\rho_{s}}{\rho_{g}} ...... (1)
\]

The flow rate of the water model could be calculated by the Eq. (2):

\[
\frac{Q}{Q_{1}} = \left( \frac{d_{1}}{d_{1}'} \right)^{5} \times \frac{\rho_{1} - \rho_{s}}{\rho_{1} - \rho_{g1}} \times \frac{\rho_{g1}}{\rho_{g}} = \sqrt{\frac{M^{5} \times \rho_{1} - \rho_{s} \times \rho_{g1}}{\rho_{1} - \rho_{g1}} \times \frac{\rho_{g1}}{\rho_{g}}} 
\]

where, \( M \) was geometric similarity ratio of the model; \( u, u_{1} \) were gas velocities (m·s\(^{-1}\)); \( Q, Q_{1} \) presented gas flows (Nm\(^{3}\)·h\(^{-1}\)); \( d, d_{1} \) stanced for nozzle diameters (mm); \( \rho, \rho_{1} \) were liquid density (kg·m\(^{-3}\)); \( \rho_{g}, \rho_{g1} \) presented gas density (kg·m\(^{-3}\)); \( g \) acted as acceleration of gravity (m·s\(^{-2}\)); the subscripts \( l, g \) were short for liquid and gas. The nomenclature with subscript (1) represent the parameters of model, and the nomenclature without subscript represent the parameters of prototype. The prototype and model parameters were shown in Table 1.

2.2. Experiment Instrument

The Fig. 1 showed the main experiment instruments, and the converter was made from plexiglass with the geometric ratio 1:4 in this research. The supersonic oxygen lance nozzle and powder injection nozzle were fabricated from brass material. In the experiment, tap water, corn oil, and compressed air were used to represent molten metal, liquid slag and blowing gas, respectively. Eight porous plugs were adopted to simulate the bottom-blowing process. The bottom-blowing arrangement of the model was the same as that of the prototype. Before the water experiment, both water and oil would be added into the plexiglass model according to the Table 1, and then the compressed air would be blown into. After the flow rate of the water model could be calculated by the Eq. (2):

\[
\frac{Q}{Q_{1}} = \left( \frac{d_{1}}{d_{1}'} \right)^{5} \times \frac{\rho_{1} - \rho_{s}}{\rho_{1} - \rho_{g1}} \times \frac{\rho_{g1}}{\rho_{g}} = \sqrt{\frac{M^{5} \times \rho_{1} - \rho_{s} \times \rho_{g1}}{\rho_{1} - \rho_{g1}} \times \frac{\rho_{g1}}{\rho_{g}}} 
\]

tracer element concentration and mixing time would be measured, and other details of experiment procedure could be found in the literature 11. For measuring the tracer element concentration in the bath, three conductivity electrodes (A, B and C) had been installed at different locations, as shown in Fig. 1. During each water experiment, fifty milliliters KCl solution was used as tracer to change the initial conductivity of bath, and the injection location of KCl was on the front end of the funnel, which delivered compressible air into the powder injection nozzle. In this paper, the mixing time was defined as that when the tracer concentration at the monitor points reached 99% of the average tracer concentration in the bath. The \( T_{A}, T_{B}, T_{C} \) presented the mixing times measured by three conductivity electrodes, respectively. The mean mixing time (\( T_{M} \)) was achieved as an arithmetical mean value by Eq. (3):

\[
T_{M} = \frac{T_{A} + T_{B} + T_{C}}{3} \]

As depicted in the Fig. 2, the injection nozzle were installed 150 mm or 300 mm below the surface of molten bath (red line), based on the angle between nozzle and mid-line being 0°, 22.5°, or 45°. That means there were six kinds of powder injection arrangement. In this paper, the injection arrangement would be described as A (injection angle)-B (injection depth). For example, the 22.5–150 arrangement means the injection nozzle would be installed 150 mm below the surface of molten bath with the angle being 22.5°.
The oxygen lance height, top-blowing and bottom-blowing flow rate were constants in all experiments. The gas flow rates and lance heights of prototype and model were listed in Table 2.

3. Numerical Model

To analyze the effects of different powder injection arrangements on flow field characteristics of molten bath, a 3-D model was developed with multi-phase flow distribution. In numerical simulation process, the oxygen lance height, side-blowing top-blowing and bottom-blowing rate was 1 500 mm, 120 Nm$^3$/h, 18 000 Nm$^3$/h and 300 Nm$^3$/h, respectively, and the assumptions about numerical model were presented as follows:

(1) All chemical reactions or powder injection process were not taken into consideration;
(2) The gas phase was regarded as compressible Newtonian fluid, while the liquid slag and molten steel were addressed as incompressible Newtonian fluid;
(3) A no-slip condition was applied to all of the walls, and the standard wall function was used to solve the averaged velocity near the wall.

3.1. Governing Equations

In the numerical simulation process, the VOF model had been applied to calculate the variation of free interface sharp of multi phases. The fluid phase was defined as a single continuum ($\alpha_i$), which did not interpenetrate with other phases. Therefore, the average value of $\alpha_i$ phase in a cell presented the volume fraction of the cell occupied by the fluid. The $i$th fluid’s volume fraction in the cell was denoted as $\alpha_i$, using $\alpha_i$ to control each phase volume within the domain.$^{15,16}$ As a result, three conditions could be defined as follows:

$\alpha_i=0$ The cell was empty (of the $i$th fluid).
$\alpha_i=1$ The cell was full (of the $i$th fluid).
$0<\alpha_i<1$ The cell contained the interface between the $i$th fluid and one or more other fluids.

In the VOF model, the fluids phases in the computational domain and sum of all volume fractions must be one in every cell. Moreover, both effective density $\rho$ (kg·m$^{-3}$) and effective viscosity $\mu$ (Pa·s) were solved by the weighted averaging method, according to the volume fraction of each phase. The continuity, momentum, and energy equations would be expressed as:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0 \quad \cdots (4)$$

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = - \frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + f_i \quad \cdots (5)$$

$$\frac{\partial (\rho c_T T)}{\partial \tau} + \frac{\partial (\rho u_i c_T T)}{\partial x_j} = u_j \frac{\partial p}{\partial x_j} + \tau_{ij} \frac{\partial u_i}{\partial x_j} + k_{ij} \frac{\partial^2 T}{\partial x_j} \quad \cdots (6)$$

For the transport equation, the average effective density ($\rho$) effective viscosity ($\mu$) and specific heat ($c_p$) were determined as:

$$\rho = \alpha_g \rho_g + \alpha_l \rho_l + \alpha_m \rho_m \quad \cdots (7)$$

$$\mu = \alpha_g \mu_g + \alpha_l \mu_l + \alpha_m \mu_m \quad \cdots (8)$$

$$c_p = \alpha_g c_{p,g} + \alpha_l c_{p,l} + \alpha_m c_{p,m} \quad \cdots (9)$$

where, $u_i$ and $u_j$ were the velocity components in the direction of $i$ and $j$, respectively (m·s$^{-1}$); $p$ was the pressure (Pa); $g$ was the gravity acceleration (m·s$^{-2}$); $T$ was the temperature (C); $c_p$ was the specific heat (J·kg$^{-1}$·K$^{-1}$); $\tau_{ij}$ and $k_{ij}$ were the viscous stress tensor (N·m$^{-2}$), and effective thermal conductivity (W·m$^{-1}$·K$^{-1}$), respectively; The subscripts g, l, and m represented the gas-phase, liquid slag and molten steel, respectively.

Based on the VOF transport equation,$^{17,18}$ the standard k-ε model was adopted to describe the turbulence kinetic energy ($k$) and its dissipation rate ($\varepsilon$), which could be calculated by following equation:

$$\frac{\partial (\rho k)}{\partial \tau} + \frac{\partial (\rho ku_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \frac{\partial k}{\partial x_j} \mu \frac{\partial u_i}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M \quad \cdots (10)$$

$$\frac{\partial (\rho \varepsilon)}{\partial \tau} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \mu \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_3\varepsilon) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \quad \cdots (11)$$

In the Eqs. (10) and (11), the $G_k$ and $G_b$ were the generation of turbulence kinetic energy (kg·m$^{-1}$·s$^{-3}$), due to the mean velocity gradient and the buoyancy, respectively. $Y_M$ represented the contribution of the fluctuating dilatation (kg·m$^{-1}$·s$^{-3}$) in compressible turbulence to the overall dissipation rate. The $\sigma_k$ and $\sigma_\varepsilon$ were the turbulent Prandtl numbers for $k$ and $\varepsilon$, respectively. The turbulent viscosity ($\mu_t$) was achieved by combining $k$ and $\varepsilon$ as follows:

$$\mu_t = \rho C_{\mu} \frac{\varepsilon^2}{k} \quad \cdots (12)$$
where $C_1$, $C_2$, $C_p$, $\sigma_s$, and $\sigma_e$ were constants and had the following default values: $C_1=1.44$, $C_2=1.92$, $C_p=0.09$, $\sigma_s=1.0$, $\sigma_e=1.3$.

3.2. Computation Methodology

The geometry ratio of converter model was 1:1 in the numerical simulation, due to the 150 t vanadium extract converter. The calculation domain of the model included five nozzles oxygen lance, molten bath, side-blowing and bottom-blowing nozzles, and the space from oxygen nozzle tip to molten steel surface. The side-blowing nozzle had the same parameters for all side-blowing arrangements. The thermo-physical properties and specific parameters of multi-phase model were depicted in Tables 1 and 3, respectively.

The inlet boundary inlet of top-blowing, side-blowing and bottom-blowing were used mass flow inlet, and pressure-outlet boundary condition was adopted for the outlet position of converter (Gauge pressure $=101325$ Pa). Initially, the simulation model was calculated with no oxygen or nitrogen blowing through oxygen lance, side-blowing or bottom-blowing nozzles. Because of the large gradient of velocity at the Laval nozzle, the initial time step size was $10^{-5}$ s. And then an adaptive method was chosen for the time steps with the global Courant number being 1. During numerical simulation process, the pressure-velocity was coupled in PISO scheme with the unsteady solution mode. The Body Force Weighted discretization and Geometric reconstruction scheme were used for calculating the pressure based on the gravity of molten bath and the interface interpolation method, respectively. The other equations were calculated by second-order upwind schemes. Moreover, for each numerical simulation case, the residuals of dependent variables would be addressed as convergent with the residual errors of energy and other variables being less than $10^{-6}$ and $10^{-3}$, respectively.

3.3. Mesh Sensitivity Test

To analyze the mesh sensitivity of the simulation model, the mesh of vanadium converter was addressed as following levels: fine mesh (180 342 cells), medium mesh (143 171 cells), and coarse mesh (100 547 cells). The average flow velocity profile of molten bath for three kinds of mesh levels was depicted in Fig. 3.

In order to achieve an accurate result, there were 100 monitor points had been selected randomly to measure and calculate the average flow velocity of molten bath, during numerical simulation process. When the variation of flow velocity was relatively small or fluctuated within a stable section, the quasi-steady-state flow field was developed.

The average percentage of variation of the average flow velocity calculated by the coarse and medium mesh level was 9.2%. For the medium and fine mesh levels, the variation was negligible (less than 1%). However, the computational time required for the fine mesh was approximately 1.7 times that for the medium mesh. Therefore, the result calculated by the medium mesh was chosen to research and discuss in this paper.

4. Results and Discussions

4.1. Analysis of Water Experiment

The mixing time could represent the stirring effect of molten bath, and the stirring effect improves with the mixing time reducing. The relation between the mixing time and the side-blowing rate has been shown in the Fig. 4, under the same lance height, top-blowing and bottom-blowing rate.

![Flow velocity of molten bath for three mesh levels.](image)

**Fig. 3.** Flow velocity of molten bath for three mesh levels.

![The mixing time of water experiment with various side-blowing rate and arrangement.](image)

**Fig. 4.** The mixing time of water experiment with various side-blowing rate and arrangement.

<table>
<thead>
<tr>
<th>Table 3. Thermo-physical properties of three-phase.</th>
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<tr>
<td>Density/(kg·m⁻³)</td>
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<tr>
<td>Viscosity/(kg·m⁻³·s⁻¹)</td>
</tr>
<tr>
<td>Thermal conductivity/(W·m⁻¹·K⁻¹)</td>
</tr>
<tr>
<td>$C_p$(J·kg⁻¹·K⁻¹)</td>
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<tr>
<td>Temperature/(K)</td>
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The mixing time of six kinds of bottom-blowing arrangements are different. Under the combined-blowing condition, the mixing time decreases with rising side-blowing rate. Compared with the average mixing time with different arrangements, the 45–300 arrangement obtains the shortest average mixing time being 38.8 s, and the 0–150 arrangement achieves the longest average mixing time being 47.4 s, at the tested conditions. When the side-blowing flow rate is range from 0.98 to 1.96 Nm³/h, the 45–300 arrangement also has the shortest mixing time, which proves the stirring effect of molten bath would be the best with 45–300 arrangement. To research the relationship between the mixing time and the side-blowing rate, the average mixing time of all side-blowing arrangement has been analyzed. Based on the result, the average slopes of the linear regression are 15.2, 9.5, 6.1 and 2.1, with flow rate in the range of 0.98 to 1.23 Nm³/h, 1.23 to 1.47 Nm³/h, 1.47 to 1.72 Nm³/h and 1.72 to 1.96 Nm³/h, respectively. That means the downtrend of mixing time would be suppressed with flow rate increasing, at the tested condition.

**4.2. Analysis of Numerical Simulation**

Figure 6 shows the flow velocity distributions on the vanadium converter cross section at 54 s with different side-blowing arrangements, and the section is 225 mm below the molten bath surface. Different colors represent different flow velocities, with maximum velocity being addressed as red and minimum velocity being blue. The detail values are shown in the figure.

As shown in Fig. 6, the flow velocity near the converter wall is quite low with none side-blowing arrangement. Based on the result, the flow velocity, which region is near the side-blowing nozzle, would increase obviously As the arrangement changing, this flow velocity pattern is more-or-less preserved. The average flow velocity of molten bath with 0–150, 0–300, 22.5–150, 22.5–300, 45–150 and 45–300 arrangement is 0.071 m/s, 0.073 m/s, 0.074 m/s, 0.076 m/s, and 0.080 m/s, respectively. Compared with the six kinds of side-blowing arrangement, the average flow velocity of molten bath with the 45–300 arrangement is the biggest, so is the area surrounded by the 0.03 m/s isovelocity. The bigger average flow velocity is, the larger area is surrounded by 0.03 m/s isovelocity, and the smaller area of the 0.01 m/s isovelocity is. At the tested condition, when the injection angle of side-blowing nozzle is 0°, 22.5° and 45°, the average flow velocity is 0.072 m/s, 0.075 m/s and 0.079 m/s, respectively. Moreover, the average flow velocity is 0.074 and 0.076 with the nozzle depth being 150 mm and 300 m, respectively. Based on the results of water experiment and numerical simulation, it seems that the flow velocity of molten bath would improve when the side-blowing nozzle is inserted far from bottom-blowing nozzle and bath surface.
As analyzed in water experiment, the velocity interference between side-blowing jet and bottom-blowing bubbles would suppress the stirring ability of side-blowing. Although velocity interference is hard to detect without appropriate tracer material in water experiment, the flow field of molten steel calculated by the numerical simulation could easily show this phenomena. The **Fig. 7** present the flow velocity distributions on longitudinal section at different injection angle in the molten bath.

As shown in the **Fig. 7**, there are two main low-velocity regions (the flow velocity is less than 0.01 m/s) in molten bath, which is addressed as region B and region D. The region B is the outcome of combined action of top-blowing and bottom-blowing, and the side-blowing seems show a little effect on this region. It is hard to analyze the effect of side-blow injection angle on the volume of region D, because the bottom-blowing is also a great influence factor on the molten bath. Besides, there is low-velocity region has been formed in the molten bath with the 0–150 arrangement, which is addressed as region C. The **Fig. 8** presents the stream of molten flow with the 0–150 arrangement. Based on the result, the movement direction of molten flow, which is formed by the bottom-blowing and side-blowing, is in the opposite direction. Hence, the kinetic energy of molten bath has been removed, and the region C would be formed. As a result, the average velocity of region A with 0° side-blowing injection angle seems lower than other injection angle in the **Fig. 6**. For the 45–150 arrangement, the velocity of the region D would be improved, since the side-blowing nozzle is inserted far away from the bottom of converter. Therefore, it would take more time to let the bubbles of side-blowing rise to the bath surface, and the interaction of molten bath and side-blowing bubbles should be strengthened. As a
result, the stirring effect of molten bath is improved, and the volume of the region D is reduced.

In this paper, the zone, where flow velocity of molten steel is lower than 0.001 m/s, is defined as the velocity dead-zone, and the average flow velocity and volume of dead-zone has been shown in the Fig. 9. Based on the results, the volume of dead-zone varies oppositely with average flow velocity of molten bath. The minimum volume is 3.01 m³ generated by 45–300 arrangement with the biggest average flow velocity being 0.080 m/s, and the maximum volume is 3.52 m³ generated by 0–150 arrangement with the minimum average flow velocity being 0.071 m/s.

The result shows that appropriate side-blowing arrangement could improve the stirring ability of side-blowing jet, and suppress the velocity dead-zone volume. Comparing with six kinds of side-blowing arrangement, the 45–300 arrangement could achieve the biggest average flow velocity of molten bath being 0.080 m/s, and the minimum volume of dead-zone being 3.01 m³.

4.3. Industrial Application Research

Based on the results of water experiment and numerical simulation, the 45–300 arrangement showed the best stirring effect on molten bath in vanadium extraction process. In order to analyze the metallurgical and operation benefits of the powder injection technology, both the 45–300 arrangement and none powder injection arrangement were adopted in a 150 t vanadium extraction converter, and the powder was the iron ore with diameter being 0.75 mm. Hereafter, none powder injection arrangement would be addressed as none arrangement. There were 160 heats collected in the industrial application research, including 80 heats with 45–300 arrangement and 80 heats with none arrangement, and the operation conditions were same with both the 45–300 and none arrangements in melting process. Semi-steel component, vanadium extraction rate and T. Fe content in the slag were studied in this research. The semi-steel, which is before and after melting process, would be defined as semi-steel A and semi-steel B, respectively.

The average components and temperatures of semi-steels are shown in Table 4. The initial conditions of semi-steel A is stable, which means the effect of semi-steel A conditions on the vanadium extraction rate could be negligible. Moreover, the smelting process for the vanadium extraction is same with both kinds of powder injection arrangement.

Comparing with none arrangement, the content of vanadium in semi-steel B is dropped by 0.011 mass% with the 45–300 arrangement, and the vanadium extraction rate in the converter is improved by 4.8% from 81.0% to 85.8% with the temperature of semi-steel B increasing little. Figure 10 illustrates the distribution of vanadium in semi-steel B using two kinds of powder injection arrangements for vanadium extraction. When the none arrangement is used, the content of vanadium in semi-steel B distributes from 0.027 mass% to 0.061 mass%. And the content of vanadium in semi-steel B is from 0.021 mass% to 0.046 mass% with the 45–300 arrangement. Therefore, the 45–300 arrangement would decrease the content and fluctuation range of vanadium content in semi-steel B, which means the powder injection technology could improve the stability of melting process.

V₂O₅, T. Fe, M. Fe, and FeO contents in slag are shown in Fig. 11. Compared with the none arrangement, stirring effect of molten bath would be enhanced with 45–300 arrangement. The content of V₂O₅ is increased by 1.4 mass%, the content of FeO is decreased by 2.1 mass%, and the content of T. Fe loss is reduced by 2.0 mass% in slag. However, the content of M. Fe in slag is increased by 0.7 mass%. During the vanadium extraction process, fluidity of slag would be reduced with FeO content dropping. As a result, the M. Fe is hard to be transmitted into molten bath, because the slag becomes sticky due to the reduction of FeO.

Table 4. Average values analysis of semi-steels with different powder injection arrangement.

<table>
<thead>
<tr>
<th>Label</th>
<th>None arrangement</th>
<th>45–300 arrangement</th>
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<tbody>
<tr>
<td>C (mass%)</td>
<td>4.46</td>
<td>4.46</td>
</tr>
<tr>
<td>V (mass%)</td>
<td>0.231</td>
<td>0.232</td>
</tr>
<tr>
<td>Semi-steel A Si (mass%)</td>
<td>0.21</td>
<td>0.22</td>
</tr>
<tr>
<td>Ti (mass%)</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>1 586</td>
<td>1 585</td>
</tr>
<tr>
<td>C (mass%)</td>
<td>3.61</td>
<td>3.60</td>
</tr>
<tr>
<td>Semi-steel B V (mass%)</td>
<td>0.044</td>
<td>0.033</td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>1 659</td>
<td>1 650</td>
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Fig. 9. The relationship between the average flow velocity and velocity dead-zone.

Fig. 10. Distribution of vanadium contents in semi-steel B.
Based on the results, it seems that with the iron ore powder injected into the molten steel, the temperature of molten bath could be controlled better, which is good for the thermodynamics condition of vanadium extraction. At the same time, the side-blow method would improve the stirring effect of molten bath and the mass transfer of vanadium, which agrees with the results of water experiment and numerical simulation. Above all, the powder injection technology could inhibit the condition that the carbon–oxygen reaction well, and achieve both metallurgical and operation benefits.

5. Conclusions

In this paper, the effect of side-blowing arrangement on flow field of molten bath has been researched, and different flow rates, injection angles and injection depths of side-blowing nozzle have been adopted in the water experiment and numerical simulation. The mixing time, average flow velocity and velocity dead-zone is used to analyze the suitable side-blowing arrangement. With the industrial application research, an optimum side-blowing arrangement is determined for 150 t vanadium extraction converter. The main results of this study are summarized as follows:

(1) In order to take full advantage of side-blow stirring ability, the side-blowing nozzle should be inserted far from bottom-blowing nozzle as much as possible, and the molten bath can be stirred more intensively, when the distance between side-blowing nozzle and bath surface increases, at the tested conditions.

(2) Compared with the six kinds of side-blowing arrangement, the 45–300 arrangement could achieve the biggest average flow velocity of molten bath being 0.0329 m/s, and the minimum volume of dead-zone being 1.90 m³.

(3) The 45–300 arrangement can accelerate the smelting process in 150 t vanadium extraction converter. Compared with none side-blowing arrangement, the content of vanadium in semi-steel B with 45–300 arrangement is 0.033 mass% and vanadium extraction rate is increased by 4.8%. The content of V₂O₅ is increased by 1.4 mass%, the content of FeO is reduced by 2.1 mass% and the content of T. Fe loss is dropped by 2.0 mass% in slag. However, slag becomes sticky due to the reduction of FeO, which makes the content of M. Fe in slag be increased by 0.7 mass%.

Acknowledgements

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