On a Reaction Model of the Oxygen Steelmaking Process*

By Akira FUKUZAWA,** Ryuichi NAKAGAWA,** Shiro YOSHIMATSU** and Takuya UEDA**

Synopsis

A mathematical model (resistance model) has been developed by assuming that reaction rates of the oxygen steelmaking process are limited by the mass transfer which is affected by the bath mixing caused by the jetted oxygen and the generated CO gas. The characteristics of this model are discussed through the comparison between the NRIM continuous steelmaking process and BOF process for the probable range of values of resistance coefficients and oxygen delivery ratio, both being the essential factors in the model. As a consequence, it becomes clear that the resistance coefficient is independent on the furnace size and takes practically constant value for each reaction.

Simulation of single (1 lance) and 2 (2 lances) staged co- and counter-current continuous steelmaking processes, BOF and VOD on the basis of this model is found to reproduce the characteristics of each process.

From the foregoing, it can be concluded that the assumption that the gas flow rates have an important role on the bath mixing can provide a valuable aid to understand the steelmaking reaction kinetics.

I. Introduction

A mathematical model is required to represent the behavior of the actual system under various conditions, and especially for the development of a new system. The development of the mathematical model provides means for the comprehension of the system behavior, gives orientation for the designing and modification of the system and also makes it easy to investigate the control strategy of the system. The well-designed mathematical model can minimize time and cost of development and operation of the system.

This concept is not exceptional for the development of the model of oxygen steelmaking processes including NRIM continuous steelmaking process. In this case the most important matter to be considered is how to represent the dynamic variation of C, O and (FeO) with blowing time. Here, the model used for the simulation of NRIM continuous steelmaking process in which the rate limiting step is mass transfer (resistance model) is discussed to clarify its characteristics and limits to what extent this model satisfies the above requirements. The possibility of its application is also examined.

II. Characteristics of the Resistance Model

1. Construction of the Model

As in the previous paper, present model stems from the fact that the rates of steelmaking reactions are limited by the mass transfer, and assumes the following:

(1) One oxygen lance makes one back-mixing tank, where compositions in metal and slag are uniform, respectively, and the temperatures of metal, slag and exhaust gas are equal.

(2) The mixing characteristics of the continuous steelmaking process with several lances installed in series like NRIM process can be represented by the back-mixing tanks in series the number of which is equal to that of lances.

(3) A part of blown oxygen is captured by the slag phase as FeO, and the rest is absorbed into the metal phase.

(4) Steelmaking reactions are controlled by the mass transfer; the reaction rate is in proportion to the difference in the reactant concentrations between steel bath and slag or gas phase. The rate is in inverse proportion to the transfer resistance.

(5) The transfer resistances are assumed inversely proportional to the evolution rate of exhaust gas generating in CO reaction, and to the sum of the rates of exhaust gas evolution and oxygen blowing in slag-metal reactions.

(6) Concentrations of C and O at the gas-metal interface are in equilibrium with \( P_{CO} = 1 \) atm in CO reaction. The rates of transfer of the two elements to the interface satisfy the stoichiometry of \( C + O = CO \) reaction and transfer resistances to both elements are equal.

(7) In the slag-metal reactions, the reduction of \( (FeO) \) proceeds according to the difference between the oxygen concentration in the metal in equilibrium with \( (FeO) \) and that of metal bath. The oxidations of \( Si, Mn \) and \( P \) proceed by the difference between the concentrations in the metal in equilibrium with slag and those of metal bath, accompanying the reduction of \( (FeO) \). When the concentration difference becomes negative, reverse reactions proceed with mass transfer as rate controlling step.

Mass balance for one lance in the continuous steelmaking furnace can be represented by the following equation on the basis of the foregoing assumptions:

\[
\frac{dW_iC_{j\text{out}}}{dt} = Q_{in}C_{j\text{in}} - Q_{out}C_{j\text{out}} - \Delta C_j/R_j \quad \cdots (1)
\]

where, \( \Delta C_j = C_{j\text{out}} - C_{j\text{in}} \).

The resistance model is to solve the above simultaneous equations (the number of which is equal to that of object elements) in accordance with equilibrium equations, heat balance equations, and initial and boundary conditions.

2. Oxygen Delivery Coefficient

Oxygen delivery coefficient, \( X \), is defined as the


** National Research Institute for Metals, Nakameguro, Meguro-ku, Tokyo 153.
ratio of the amount of oxygen consumed for the formation of (FeO) to that of oxygen blown. This coefficient can be regarded as a function of the blowing condition. When hard blow operations are made by decreasing the lance height or the nozzle diameter, the value of \( X \) decreases since the penetration depth of oxygen jet into the metal bath increases. Reverse is the case for soft blow operations. In the simulation of the NRIM continuous steelmaking process,\(^1\) this coefficient was assumed constant. Treating this process as a constant parameter system did not bring any trouble in the simulation because the variation of the furnace condition was less in the continuous operation. Variation of the oxygen delivery coefficient from 0.3 to 0.9 in the simplified continuous steelmaking model for Fe–C–O system resulted in the changes in \( C \) and temperature, but did not make the computer processing quit.

For the simplification of the model, the direct reaction between \( O_2 \) and elements in the metal are not taken into account except for the oxidation of iron. In order to put the oxygen absorption mechanism explicitly into the model, area of reaction interface, mass transfer of reactants and products to and from the reaction interface, and reaction site should be considered. This is too complicated to make a practical model, so that the model on simple assumptions as stated in II. \( I \) is adopted. The transfer resistance \( R \) used in the model may be regarded the synthesis of the resistances involved in the above mentioned elementary steps.

3. Resistance Coefficient of Decarburization Reaction

The characteristic of the reaction of \( C \) removal is in its self-propagation ability. In the water model of gas jet impinging test, the existence of a violently moving cavity and many numbers of bubbles around the cavity can be observed. In the actual furnace, these bubbles seem to offer sites as suitable as other sites for CO boil of super saturated \( C \) and \( O \). The degree of this saturation is in terms of \( P_{CO} \) as high as tens of atm. The bubble growth, therefore, is extremely fast and the mixing around the cavity is several times stronger than that of water model, and hence generates more bubbles, with which the propagation of the cavity to the surrounding region also seems to be stronger. Through these processes, it can be considered that one bubble growth generates other bubbles and promotes the CO reaction. This a kind of self-propagation (positive feed back) is the common characteristics which can be observed in various kinds of steelmaking processes where wide range of the oxygen feed rate and the decarburization rate closely satisfy the stoichiometrical relation.

The increase of the bath mixing through the above-mentioned process brings the decrease of the mass transfer resistance. In the model this is represented in assumption (5), on which the denominator of the third term of the right side in Eq. (1) is defined as follows:

\[
R_{\text{CO}} = \alpha_{\text{CO}} V_{\text{CO}} \quad \text{........................(2)}
\]

To examine the resistance coefficient \( \alpha_{\text{CO}} \) of decarburization, Eq. (1) can be rewritten as follows, since the accumulation rate is zero at steady state, where input and output rates of metal are assumed equal,

\[
\begin{align*}
Q(C_{\text{in}} - C_{\text{out}}) &= \frac{JC}{R_{\text{CO}}} \quad \text{....................(3)} \\
O_2{\text{in}} - QO_{\text{out}} - O_{S'M} &= \frac{JO}{R_{\text{CO}}} \quad \text{....................(4)}
\end{align*}
\]

where, \( C = C - C^* \), \( O = Q - O^* \), \( C = C_{\text{out}} \), \( O = O_{\text{out}} \) and \( O_{S'M} \) is oxygen consumed for slag-metal reactions. As Eqs. (3) and (4) satisfy assumption (6), one gets for the transfer rates of the two elements,

\[
\frac{JC}{R_{\text{CO}}} = \left(\frac{12}{16}\right)JO \frac{R_{\text{CO}}}{R_{\text{CO}}} \quad \text{....................(5)}
\]

For the CO generation rate \( V_{\text{CO}} \), one has

\[
V_{\text{CO}} = \frac{JC}{R_{\text{CO}}} + JO \quad \text{....................(6)}
\]

Substituting Eq. (6) into Eq. (2), and rewriting for \( \alpha_{\text{CO}} \) give

\[
\alpha_{\text{CO}} = \frac{JC + JO}{\frac{JC}{R_{\text{CO}}}} = \left(\frac{28}{12}\right)JC = \left(\frac{28}{16}\right)JO \quad \text{....................(7)}
\]

Equation (8) is obtained by regarding Eq. (5).

From the above consideration it becomes clear that \( \alpha_{\text{CO}} \) is the summation of \( JC \) and \( JO \), and that this model assumes that the CO reaction proceeds so as to keep the difference in concentration between the bulk and the CO bubble interface constant. Here, \( JO \) corresponds to so called excess oxygen in BOH. The concentration of oxygen in equilibrium with CO bubble can be derived from Eq. (5) and equilibrium constant \( K_{\text{CO}} = P_{\text{CO}}/(C^*O^*) \) with assumption (6) \( (P_{\text{CO}} = 1 \text{ atm}, K_{\text{CO}} = 4.55 \times 10^{-8}, 1500^\circ \text{C}) \) as follows:

\[
O^* = \left(\frac{0 - 4C^*}{3} + [0 - 4C^*/3]^2 + 16/[3K_{\text{CO}}]^{1/2}\right)/2 \quad \text{....................(9)}
\]

The values of \( \alpha_{\text{CO}} \) calculated with this equation by using the data of \( C - Q \) relation in LD converter\(^3\) and also in the final stage of the NRIM process are listed in Table 1. These values agree well with the value \( \alpha_{\text{CO}} = 1.8 \times 10^{-4} \) obtained by a optimization method described in the previous article.\(^2\) From Table 1, \( \alpha_{\text{CO}} \) has a tendency to increase as \( C \) becomes lower. This seems to suggest that to treat \( \alpha_{\text{CO}} \) as a distributed-parameter system gives more accurate simulation for low \( C \) range. Moreover, \( \alpha_{\text{CO}} \) is influenced by the blowing condition: In the hard blow \( \alpha_{\text{CO}} \) becomes smaller because \( JO \) is reduced, whereas in the soft

<table>
<thead>
<tr>
<th>Table 1. ( \alpha_{\text{CO}} ) calculated with actual data</th>
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<tbody>
<tr>
<td>LD process(^b)</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Actual (%)</td>
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<tr>
<td></td>
</tr>
<tr>
<td>Calculated (%)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>( \alpha_{\text{CO}} )</td>
</tr>
</tbody>
</table>
blow $\alpha_{\text{eq}}$ takes larger value.

4. Resistance Coefficient of Desiliconization Reaction

Resistance coefficient of desiliconization reaction ($\alpha_{\text{eq}}$) in one lance continuous steelmaking furnace is derived as follows: First, $\alpha_{\text{eq}}$ equilibrated with slag, is assumed negligible since $\alpha_{\text{eq}}$ is small and its temperature dependency is also small. Then, by substituting this assumption into the 3rd term of right side of Eq. (1), Eq. (1) can be rewritten at steady state as

$$0 = Q(Si_{\text{in}} - Si_{\text{out}}) - Si_{\text{out}}(V_{\text{CO}} + V_{O_2})/\alpha_{\text{eq}}$$

(10)

The residual ratio of Si ($\phi_{\text{Si}}$) is

$$\phi_{\text{Si}} = Si_{\text{out}}/Si_{\text{in}} = Q/(Q + (V_{\text{CO}} + V_{O_2})/\alpha_{\text{eq}})$$

$$= 1/[1 + 1/(QR_{\text{eq}})]$$

(11)

Rearranging for $\alpha_{\text{eq}}$ gives

$$\alpha_{\text{eq}} = (V_{\text{CO}} + V_{O_2})/(Q(1/\phi_{\text{Si}} - 1))$$

(12)

In the case when the metal sampling at each lance is difficult in a trough type continuous steelmaking furnace with $n$ lances, $\alpha_{\text{eq}}$ is determined as follows: By assuming that the hold-up weight, oxygen blowing rate, and CO generating rate per one lance are one $n$-th of their totals, respectively, $\phi_{\text{Si}, i}$ ($i = 1 \sim n$) for each lance becomes equal as evident in Eq. (11), so that the over-all $\phi_{\text{Si}}$ of the furnace becomes as a function of $\phi_{\text{Si}, i}$ as follows:

$$\phi_{\text{Si}} = Si_{\text{out}}/Si_{\text{in}} = Si_{\text{out}}^{i}/Si_{\text{in}}^{i} \quad \text{for} \quad i = 1 \sim n$$

$$= (\phi_{\text{Si}, i})^n$$

(13)

By substituting this $\phi_{\text{Si}, i}$ into Eq. (12) instead of $\phi_{\text{Si}}$, $\alpha_{\text{eq}}$ can be obtained.

The values of $\alpha_{\text{eq}}$ calculated from the operational data of NRIM¹ and Bethlehem Steel Corp.² continuous steelmaking processes by the foregoing relations are listed in Table 2. In the former case Eq. (13) is applied and in the latter Eq. (12) is directly used by adopting the analysis of the first 2 holes. As these values are similar to those searched by the complex method in the previous paper³ and their dispersion is small, the simulation of the desiliconization on the assumption, $\alpha_{\text{eq}} = 0$, is feasible.

Then, for the calculation of $\alpha_{\text{eq}}$ of LD converter operation Eq. (1) is arranged as follows by eliminating the terms of input and output of the hot metal and by assuming $Si_{\text{eq}} = 0$:

$$dW/\text{dt} = -Si/R$$

(14)

where $Si = Si_{\text{out}}$. By assuming that $W$ is constant and $V_{\text{CO}} = 0$ at the beginning of the blowing, one obtains

$$WdSi/\text{dt} = -SiV_{O_2}/\alpha_{\text{Si}}$$

(15)

Solving this with the initial condition of $Si = Si_0$ at $t = 0$, yields

$$\phi_{\text{Si}} = Si/Si_0 = \exp(-t/T_c)$$

(16)

where, $T_c = \alpha_{\text{Si}}W/V_{O_2}$ (min).

Then, one has

$$\alpha_{\text{Si}} = -V_{O_2}/(W\ln \phi_{\text{Si}})$$

(17)

Several numbers of desiliconization curves selected from the observation on LD process operations⁵–⁷ are plotted for their time residual ratio relation in Fig. 1. Curves in this figure are calculated from Eq. (16) by varying $T_c$. In Fig. 1, observed values tend to take a lower value of $T_c$ with elapsing time. This is because the decarburization reaction is neglected in the calculation. Therefore, better approximation will be attainable by considering the increase of $V_{O_2}$ with time. It can be said from the foregoing that the decarburization curve for LD process tends to decrease faster than the exponential one determined by $V_{O_2}$. $\alpha_{\text{Si}}$ of every plot in Fig. 1 calculated by Eq. (17) is in the range of 0.0075 to 0.0185, and mean is 0.0113. These values are larger than those for the continuous steelmaking as shown in Table 2. The furnace shape or blowing condition will be the cause of this difference.

5. Comparison between C- and Si-removal

The residual ratio of decarburization reaction in the continuous steelmaking is derived by substituting Eqs. (2) and (8) into Eq. (3) as

$$\phi_c = C_{\text{out}}/C_{\text{in}} = 1 - 12(V_{O_2}/28C_{\text{in}}Q)$$

(18)

Naming $A$, which is defined as $A = V_{\text{CO}}/Q$, as the ratio

<table>
<thead>
<tr>
<th>Process</th>
<th>NRIM</th>
<th>Bethlehem Steel⁶</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>51</td>
<td>53</td>
</tr>
<tr>
<td>Metal rate (t/min)</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td>$O_2$ blowing rate (kg/min/lance)</td>
<td>0.8</td>
<td>0.93</td>
</tr>
<tr>
<td>Number of lances</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Sampling position</td>
<td>In</td>
<td>Out</td>
</tr>
<tr>
<td>Composition (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>3.85</td>
<td>3.05</td>
</tr>
<tr>
<td>Si</td>
<td>0.62</td>
<td>0.005</td>
</tr>
<tr>
<td>$\alpha_{\text{Si}}$</td>
<td>0.0046</td>
<td>0.0061</td>
</tr>
</tbody>
</table>
of gas- to liquid-flow rate, and substituting it into Eq. (18), one obtains

\[ \phi_{c} = 1 - \frac{12}{(28C_{\text{in}})} A_{c} \]  

(19)

Similarly, defining \( A_{\text{si}} = (V_{c0} + V_{o0})/Q \) for desiliconization reaction and putting it into Eq. (11) yields

\[ \phi_{\text{si}} = \frac{1}{1 + A_{\text{si}}/a_{\text{si}}} \]  

(20)

Relation between \( \Phi \) and \( \Lambda \) in Eqs. (19) and (20) is illustrated in Fig. 2.

Figure 2, and Eqs. (19) and (20) indicate that for decarburization \( \Phi \) decreases in proportion to the increase of \( \Lambda_{c} \), whereas for desiliconization \( \Phi \) is shown as a hyperbola with asymptotes of \( A_{\text{si}} = -a_{\text{si}} \) and \( \phi_{\text{si}} = 0 \). Namely, in the former case output carbon concentration decreases proportionally with the increase of oxygen blowing rate when the hot metal flow rate is constant and as far as the oxygen rate and decarburization rate satisfy stoichiometry. On the other hand, in the latter case the decrease of \( V_{00} \) increases the gradient of the residual ratio of Si. This means that at a constant oxygen blowing rate decarburization proceeds proportionally to the oxygen blowing rate regardless of the number of lances, while desiliconization can be proceeded more by the adoption of multi-lances installed in series as in NRIM process. The residual ratio, \( \phi_{\text{si} \ a} \) and \( \phi_{\text{si} \ n+1} \) for \( n \) and \( n+1 \) lances, respectively, are, similar to Eq. (13), given respectively by

\[ \phi_{\text{si} \ a} = \left( \frac{1}{1 + A_{\text{si}}/a_{\text{si}}} \right)^{a} \]  

(21)

\[ \phi_{\text{si} \ n+1} = \left( \frac{1}{1 + A_{\text{si}}/(n+1)a_{\text{si}}} \right)^{n+1} \]  

(22)

since the ratio of gas flow to liquid flow for one lance is \( \Lambda/n \) for the former and \( \Lambda/(n+1) \) for the latter. The comparison between these two equations by use of the binominal theorem results in \( \phi_{\text{si} \ n+1} < \phi_{\text{si} \ a} \). This indicates that the increase in the number of lances, that means the mode of flow is made closer to piston flow, is advantageous for desiliconization, though there is a practical limitation. This is similar with the case of the first order reaction in the back mix tanks in series.\(^{81} \) Actually, \( \phi_{\text{si} \ a} \) takes positive value. Therefore, the desiliconization rate as estimated by the foregoing equation is not attainable. However, it could be said that the direction how to let the slag-metal reactions proceeding continuously is given.

6. Other Resistance Coefficients

As the concentrations of Mn and P in equilibrium with slag vary widely, resistance coefficients for Mn and P can not be derived from Eq. (1) which has been applied for C and Si. Therefore, values similar to \( a_{\text{si}} \) are examined in applications described in II. 3.

Resistance coefficient, \( a_{0} \), for the decomposition of (FeO) is smaller than \( a_{\text{si}} \) in II. 3 as listed in Table 3, because it should be comparable to the value which can supply the oxygen required for the oxidation of C, Si, Mn and P. \( a_{0} \) would be easily affected by \( X \). Namely, the decrease of \( X \) leads the decrease of (FeO) or oxygen as much as that required for the oxidation of Si, Mn and P when \( X \) is greater. In this way, \( X \) and \( a_{0} \) cooperate each other.

As these values of \( a \) vary with the choice of equilibrium equation and slag temperature, it can be said that the resistance model consists of the balance between \( a \) and equilibrium equations.

As apparent from the definition, the resistance coefficient is dimensionless, and hence its value would not change widely with increasing furnace capacity as far as the mixing is kept sufficiently strong. Resistance coefficient is a function of the mixing condition as stated in II. 3. However, when the stagnant or the short-circuiting region exists in the furnace, the variation of the resistance coefficient would fall within the range as shown in II. 3 and II. 4 if correction is made for hold-up weight or flow rate.

7. Comparison between Resistances of the Continuous Steelmaking Process and Those of the LD Converter

Schematic representation of the relation between the decarburization resistance and the oxygen blowing rate in the continuous steelmaking process, and that between the decarburization resistance and the time in the converter process are given in Fig. 3. In
Table 3. System parameters and operation conditions used for the simulations of oxygen steelmaking processes

<table>
<thead>
<tr>
<th>CSP 1 staged</th>
<th>CSP 2 staged</th>
<th>LD</th>
<th>VOD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Co-current</td>
<td>Countercurrent</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1st stage</td>
<td>2nd stage</td>
<td>1st stage</td>
</tr>
<tr>
<td></td>
<td>0.00015</td>
<td>0.00015</td>
<td>0.00015</td>
</tr>
<tr>
<td></td>
<td>0.003</td>
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<tr>
<td></td>
<td>0.007</td>
<td>0.007</td>
<td>0.007</td>
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<td>0.007</td>
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<tr>
<td></td>
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<tr>
<td></td>
<td>0.85</td>
<td>0.85</td>
<td>0.75</td>
</tr>
<tr>
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<td>4.55×10^4</td>
<td>4.55×10^4</td>
<td>4.55×10^4</td>
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</tr>
<tr>
<td></td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
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<tr>
<td></td>
<td>1100</td>
<td>1100</td>
<td>O. P. 1st</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>70</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>variable</td>
<td>40~38</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>1400</td>
<td>1400</td>
<td>O. P. 1st</td>
</tr>
<tr>
<td>Input rate (kg/min)</td>
<td>Metal</td>
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<td>4.0</td>
</tr>
<tr>
<td></td>
<td>O. P. 1st</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>O</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>CaO</td>
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<td>0</td>
</tr>
<tr>
<td></td>
<td>FeO</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Scrap (Fe)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

CSP : Continuous steelmaking process
a) : Hi = HL (C_{steel} + W + C_{slag} - w) \cdot T/1600, HL = 0.016
b) : Hi = HL (C_{steel} + W + C_{slag} - w) \cdot T/1600, HL = 0.016
c) : assume 1700°C constant
O. P. 1st, 2nd : outputs of the 1st and 2nd stages, respectively

On the other hand, the continuous steelmaking process, \( R_{co} \) decreases along with the increase of \( V_{o2} \) in accordance with Eq. (2) as shown in Fig. 3 (a). However, as \( V_{o2} \) approaches to the amount required for the oxidation of \( C_{in} \), the decrease of \( R_{co} \) gets smaller, and becomes an asymptote of \( R_{co} = 28a_{co}/(16Q_{C_{in}}) \). In Fig. 3 (b), decarburization rate is adopted on the vertical axis. This is the reverse of Fig. 3 (a), and as far as \( QC_{in} \) is stoichiometrically greater than \( V_{o2} \), they change proportionally to each other. However, when \( V_{o2} \) becomes smaller, the decarburization rate becomes an asymptote of \( V_{co} = QC_{in} \times 28/12 \).

On the other hand, \( R_{co} \) in the converter can be represented as shown in Fig. 3 (c) as a function of time. While the metal bath contains sufficient amount of \( C \), \( R_{co} \) remains constant at constant \( V_{o2} \). However, decrease of \( C \) during refining results in less
active CO boil and increasing value of $R_{CO}$. The increase of $V_{Ar}$ brings violent CO boil and decrease of $R_{CO}$, and shortens the refining time. The relation between $V_{Ar}$ and the decarburization rate can be represented as shown in Fig. 3 (d) as reported in many references. \(^{10-12}\)

As mentioned above, in the continuous steelmaking process the mixing is kept even in the low C range. In the converter process, however, the mixing is weakened and the resistance is increased with the decrease of C. As the increase of the resistance further lowers the decarburization rate and retards the slag-metal reaction, oxygen supply from (FeO) is also decreased and the increase of (FeO) is caused.

From the above consideration, though it is difficult to compare both processes under the same operation condition, iron loss of the continuous steelmaking process seems to be less than that of the converter process when producing a steel with a carbon range where $R_{CO}$ increases as shown in Fig. 3 (c). Moreover, since the resistance between slag and metal in the continuous steelmaking process is kept constant, the reaction involved in this process can be proceeded nearer to the equilibrium as compared with that in the converter process. As a result, the selection of slag composition becomes easier and more effective dephosphorization can be expected. For the reduction of iron loss in the converter process, the descent of the lance or AOD-like operation can be a countermeasure. As mentioned in II. 3, the descent of the lance means the decrease of $a_{CO}$. Though the contribution of Ar addition to the decarburization is hard to evaluate quantitatively, it brings the decrease of $R_{CO}$ by means of the substitution of $(V_{CO} + V_{Ar})$ in place of $V_{CO}$ in Eq. (2). When these operations are applied to the continuous steelmaking process, further reduction of the iron loss and closer attainment of the reactions to the equilibrium should be made possible.

### III. Application of Resistance Model

To investigate the validity of the resistance model with above mentioned characteristics, mathematical models of single stage (1 lance) continuous steelmaking process, two stage co- and counter-current continuous steelmaking processes, LD converter and VOD process were constructed and simulations for these processes were done. Conditions for computations and operations are given in Table 3.

The resistance coefficient of each reaction takes a similar value with what is obtained in II. 3, II. 4 and II. 6. Since cooling materials were not employed in the continuous steelmaking model, output temperature tended to be higher. Therefore, the heat loss equation is modified so as to increase heat loss when output temperature exceeds $1600^\circ$C. Equilibrium equations used here are those recommended by Gakushin\(^{13}\) and Herasymenko's equation\(^{14}\) as in the previous paper.\(^{15}\) Activity coefficients of oxides used for equilibrium calculations are mean values obtained by reading off each activity coefficient on the line of $N_{CaO}/N_{SiO}_2=3.5$ at intervals of 0.05 in the range of $N_{SiO}_2=0.05~0.3$ in the isoactivity diagrams of the system CaO-FeO-SiO\(_2\).\(^{16}\)

Output rates of metal and slag are equal to the weights which exceed the hold-up weights listed in Table 3. Flux (CaO) is assumed to dissolve into slag soon after its addition. In the converter, flux of 800 kg is assumed to dissolve within 15 min at a constant rate. In VOD process, slag formation is assumed to be completed before the operation starts.

Computers used are IBM 360/M65, HITAC 5020F and FACOM 230/75, and languages are DYNAMO and FORTRAN.

1. **Single Stage Continuous Steelmaking Process**

Compositions and temperature of output at steady state are shown in Fig. 4 at every 10 kg/min for oxygen blowing rate of 20 to 70 kg/min. Variation of each composition resembles that in the converter process. The variations in the two processes do not fully agree with each other because resistances for the two processes differ each other at low carbon range as stated in II. 7.

Low concentration of (FeO) at an oxygen rate of 20 kg/min is brought by the selective oxidation of Si and Mn. High concentration of (FeO) at 30~40 kg O\(_2\)/min is given because CO boiling is not active yet, so that the resistance becomes high. At a low carbon range corresponding to 65~70 kg O\(_2\)/min, (FeO) takes a minimum value as shown by the dotted line. Oxygen supply over this value results in the oxidation of Fe. Mn increases gradually with the increase of oxygen rate because of the high temperature at low carbon range caused by the lack of cooling materials like scrap.

2. **Two Stage Continuous Steelmaking Process**

Compositions and temperature of output from two of the continuous steelmaking furnace used in III. 1 connected in series are examined under co- and counter-current contacts of slag with metal. Mass flows in this 2 stage process are illustrated in Fig. 5. The first furnace in which the metal flows first is called as
and high in the 1st stage and the next one is called as the 2nd stage. The oxygen delivery ratio X of the 1st stage differs from that of the 2nd stage, because hard blow is supposed in the 2nd stage where the decarburization is dominant. Transfers of metal and slag from one stage to the other are assumed instantaneous. Oxygen blowing rates in the 2nd stage differ from those in the 1st one because output carbon level is aimed at 0.1%. Flux is added into the 1st stage in the cocurrent and into the 2nd one in the counter-current operation.

Variations of reactions in the furnaces are examined by changing the oxygen blowing rate stepwise in the 1st stage as shown in Table 3. Response of the cocurrent 1st stage is shown in Fig. 6. For the first several minutes after the stepwise decrease of oxygen blowing rate, (FeO) is decreased since the decarburization is held by the oxygen fed from (FeO), but after that (FeO) is increased because the resistance between slag and metal is increased due to the weakened decarburization caused by the decrease of total feed rate of oxygen. This corresponds to the maximum of (FeO) in the range of 30-40 kg O₂/min in Fig. 4. Response of C seems to be of the 1st order. Responses of Si, Mn and P would be affected, however, more by the temporary dip of (FeO) than by the change of oxygen blowing rate itself. The effect of this step change on the 2nd stage is shown in Fig. 7. Increase of C in the 1st stage is as high as 0.15%, whereas that in the 2nd stage is only about 0.1% because the increase of input C in the 2nd stage after the step change makes decarburization stronger. (FeO) also decreases by about 2%.

Responses of the 1st and 2nd stages of the counter flow operation to the step change are given in Figs. 8 and 9, respectively. Similar to cocurrent operation, remaining impurities are increased and temperature is decreased by the decrease of oxygen blowing rates. In Fig. 8, (FeO) levels off after a steep increase and then takes a little drop unlike Fig. 6. This is induced by the increase in resistance between slag and metal after the drop of oxygen blowing rate, since the input oxygen blowing rate in the 1st stage of the counter-current furnace is greater than that of the cocurrent one by the amount of (FeO) flowing from the 2nd stage. The leveling off of (FeO) is resulted from the decrease in the amount of (FeO) flowing from the 2nd stage. Responses of other elements after the step change are also complicated. Responses of only C and temperature can be detected practically. This is because Si, Mn and P have been oxidized selectively in the 1st stage.

As formerly reported,17,18 the counter-current operation of the continuous steelmaking process can provide an effective use of oxygen since it is capable of holding the oxygen potential between slag and metal high. Namely, slag low in SiO₂ and high in CaO concentration is produced in the metal outlet side, and P in the metal low in Si and Mn is removed by contacting with this slag. After that, remaining (FeO) is reacted with metal high in Si and Mn at metal inlet side to remove Si and Mn, so that (FeO) can be reduced effectively. The difference in the dephosphorization ability is also recognized by the simulation of this model, that is, P in output metal is 0.008% in the cocurrent model, in contrast to 0.004% in the counter-current one. Through the comparison that output (FeO) is about 25% in the cocurrent, but lower than 19% in the counter-current, the advantage of the counter-current is recognized in iron yield.

The cocurrent operation responds faster to reach the next steady state. However, C in the 2nd stage of the countercurrent is still increasing 70 min after

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**Fig. 5.** Mass flow of co- and counter-current models

**Fig. 6.** Response of the 1st stage of cocurrent model when oxygen input rate is step-changed from 40 kg/min to 38 kg/min

**Fig. 7.** Response of the 2nd stage of cocurrent model when oxygen input rate of the 1st stage is step-changed from 40 kg/min to 38 kg/min and that of the 2nd stage is kept constant at 37 kg/min
steal of a given carbon level. The sensitivity of the step change. This is because the propagation of the furnace behavior forms a loop in the process since in the countercurrent the variation in the 2nd stage is fed back to the 1st stage through the slag.

Variations of C and (FeO) in the 2nd stage are given in Fig. 10 when oxygen rate in the 2nd is changed, but keeping that of the 1st stage at 40 kg/min. From the figure it can be noticed that the countercurrent requires less oxygen to produce the steel of a given carbon level. The sensitivity of the output carbon level to the change of input oxygen is, however, greater. This is the same for (FeO). The sensitivity at 0.1% C is 0.037%/ (kg O₂/min) for the countercurrent but 0.061%/ (kg O₂/min) for the cocurrent, that is 1.65 times as much as that for the cocurrent. Considering that the countercurrent operation takes longer time for the stabilization, better accuracy is required for the countercurrent operation to establish a control system.

(FeO) in the 2nd stage of cocurrent operation is higher than that in the single stage because of the fact that the gas flow rate contributing to the mixing in the 2nd stage is one half of that in the single stage, so that the resistance in the 2nd stage becomes higher, and (FeO) flows in from the 1st stage. Output (FeO) from the 1st stage of the countercurrent furnace is similar to that of the single stage furnace. This also shows that higher oxygen efficiency is attainable in the countercurrent operation. The fact that output Si in the 1st stage of both types of operations are above 0.05% corresponds with the actual data in Table 2.

Temperature of the cocurrent 1st stage is lower than that of the countercurrent because of the flux addition. On the contrary, temperature of the cocurrent 2nd stage is higher than that of the countercurrent because of the higher oxygen consumption. In both cases, temperature responds simply to the variation of oxygen blowing rate, because heats of reactions as a total decrease according with the decrease of the oxygen blowing rate. Responses are close to 1st- and 2nd-orders in the 1st and 2nd stages, respectively. However, temperature stabilization in the countercurrent is slower than that in the cocurrent.

As a consequence, except for the controllability, the countercurrent operation is advantageous for the dephosphorization and oxygen efficiency. After the step change, output (FeO) of the cocurrent becomes lower, but that of the countercurrent 1st stage gets higher. Thus, the cocurrent operation may be enough under some operating conditions, depending on aimed chemical compositions or temperature. For the selection of the operation practices, combination of this model with an optimization method will present an optimum prescription. As an example, the mixing condition in the real furnace does not always agree with that obtained by a mixing model. Therefore, it would be difficult to directly apply the result obtained by the optimization to the real. Nevertheless, the result can be used as the guide line for designing and operation.

3. LD Converter

Simulation of blowing in a 10 ton LD converter under the condition listed in Table 3 is shown in Fig.
11. Two tons of scrap (100% Fe) are assumed to be melted at a constant rate for 10 min like flux melting. Oxygen delivery ratio is set at 0.95 for the first 6 min in view of the fact that the lance is held high to promote slagging, and after that at 0.85. Computations of LD converter and VOD process are carried out with the initial value of $V_{co}$ which is assumed on the basis that there exists normal boil before blowing. The value of $V_{co}$ corresponds with $-dC/dt=0.1\%$/hr, and is naturally proportional to the furnace capacity.

Comparing this figure with that in Fig. 4, C and (FeO) at $O=0.02\%$ are 0.18% and 16%, respectively, in the single stage continuous steelmaking furnace, whereas those in the LD converter are 0.22% and 28%, respectively, that is, oxidation of iron is proceeding in the latter. This seems to be a disclosure of the difference in the resistance between both processes as stated in II. 7, although reservation should be made for the difference in the hold-up weights of metal and slag between both processes, even though same values are adopted for the resistance coefficient and oxygen delivery ratio.

Simulation of LD converter process treats the unsteady state phenomena such as semi-batch operations which impose many constraints on carrying out calculations. In addition, approximations are made that the basicity is III. 5 and melting rates of flux and scrap are constant. Nevertheless, Fig. 11 reproduces the operational results of LD converter well. This seems to imply that the resistance model can be applied to oxygen steelmaking processes under various conditions.

4. VOD Process

Through the simulation of VOD process applicability of the resistance model to the vacuum refining process has been examined. The simulation was carried out only for Fe–C system which is the base in the oxygen steelmaking process, and as input data Kuwano’s$^{(9)}$ experiment No. 106 where 100 kg high frequency induction furnace was used was referred. As the reaction proceeds under reduced pressure, the computation was done by substituting $K_{co}/P_{co}$ in place of $K_{co}$ into Eq. (9), which gives the equilibrium oxygen concentration at gas-metal interface. Oxygen efficiency was assumed 90%.

Computed results when 2 levels each of $a_{co}$, X and $K_{co}/P_{co}$ were given are shown in Fig. 12. $K_{co}/P_{co}=1\times10^8$ and $5\times10^8$ roughly correspond to $P_{co}=1/20$ and $1/100$ atm, respectively. Pressure changes in the actual furnace, but it is assumed constant here. The figure indicates the part where decarburization rate is going to decrease. Open circle in Fig. 12 represents the value observed in No. 106 experiment. Despite marked difference in the operating conditions between high frequency induction stirring and gas-jetting under reduced pressure, it would be also possible to simulate VOD process by the selection of $a_{co}$, X and $P_{co}$ levels.

The followings can be noticed from Fig. 12. The increase of $a_{co}$ retards decarburization and final $C$ level is held high (1→2). According with the decrease of X, decarburization curve moves left (2→3). The increase of $K_{co}/P_{co}$ or the decrease of $P_{co}$ produces a linear decarburization to lower $C$ level and then sharply drops the decarburization rate (3→4). Comparing curve No. 1 with No. 4 shows that $C$ is made lower by the harder bath mixing than by reducing the pressure. To get low $C$ steel fast, therefore, the operation procedure should have the values of $a_{co}$, X and $P_{co}$ decreased, such as the descent of lance, lowering the pressure and the simultaneous jetting of Ar.

Fig. 11. Simulation of 10 t LD process model

Fig. 12. Computed results of VOD process when system parameters take various values
IV. Conclusion

Through the investigation of the characteristics and application of the resistance model which assumed that reactions of the oxygen steelmaking process are controlled by the gas blowing rate in the furnace, it is confirmed that the model can fully represent the characteristics of the continuous steelmaking process, LD converter and VOD process. Especially, the assumption that the bath mixing depends on the gas blowing rate is significant to comprehend the kinetics of steelmaking reaction.

Nomenclature

- \( C \): concentration (—), carbon
- \( C_p \): specific heat (kcal/kg°C)
- \( H_L \): heat loss coefficient (—)
- \( H_I \): heat loss (kcal/min)
- \( K_{CO} \): equilibrium constant of CO reaction (atm)
- \( N \): molar fraction (—)
- \( P_{CO} \): atmospheric pressure of CO bubble (—)
- \( Q \): metal flow rate (kg/min)
- \( R \): transfer resistance (min/kg)
- \( T \): furnace temperature (°C)
- \( T_C \): time constant (min)
- \( t \): time (min)
- \( V \): gas flow rate (kg/min)
- \( W \): metal hold-up weight (kg)
- \( w \): slag hold-up weight (kg)
- \( X \): oxygen delivery ratio (—)
- \( \alpha \): resistance coefficient (—)
- \( \gamma \): activity coefficient (—)
- \( \Phi \): residual ratio (—)
- \( A \): gas–liquid flow rate ratio (—)

Subscripts

- CO: metal–gas reaction
- eq: concentration in equilibrium with CO bubble or slag
- i: number of lance (tank or stage)
- in: input
- j: metal composition
- n: total number of lance (tank or stage)
- out: output
- \( O_2 \): gaseous oxygen
- S·M: slag–metal reaction

Superscript

- *: gas-metal interface

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