Effect of Iron Oxide Feeding Rate and Hot Metal Temperature on Dephosphorization Rate in Torpedo Car

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In this study, the reduction behavior of iron oxide and the effects of the iron oxide feeding rate and hot metal temperature on the dephosphorization rate were investigated in laboratory experiments and industrial plant tests with the aim of increasing the dephosphorization rate. The results are summarized as follows:

1. When the iron oxide feeding rate was 400 kg/min under a constant lime feeding rate, 61% of the iron oxide is reduced by a transitory reaction zone, while 11% is reduced by a permanent reaction in the effective reaction zone in the top slag. The remainder is not reduced and remains in the dead zone in the torpedo car in the form of iron oxide.

2. The iron oxide reduction rate in the transitory reaction zone is dependent on the hot metal temperature and iron oxide feeding rate. When the hot metal temperature was reduced from 1653 to 1563 K (∆90°C), the iron oxide reduction rate decreased by 40%. The reduction ratio decreased by 20% when the iron oxide feeding rate was increased from 200 to 400 kg/min.

3. The apparent activation energy of iron oxide reduction was evaluated as 132 kJ/mol, which is slightly smaller than the temperature dependence of the diffusion coefficient of oxygen in FeO–CaO–SiO2 slag.

4. A new mathematical model of hot metal dephosphorization in the torpedo car was developed, which considers the effect of the hot metal temperature and iron oxide feeding rate on the oxygen supply rate. The results with this model showed good agreement with actual data from the torpedo car.

KEY WORDS: dephosphorization; torpedo car; reduction of iron oxide; temperature; flux feeding rate.

1. Introduction

Hot metal dephosphorization is performed to reduce steelmaking costs, reduce the quantity of steelmaking slag, and improve steel quality. One hot metal dephosphorization process involves injection of a dephosphorization flux into the hot metal in the torpedo car. Some studies of the hot metal dephosphorization reaction have been published.1–4 However, this previous work did not clarify the role of the reduction of iron oxide, that is to say, oxygen supply from the iron oxide, in the flux injection dephosphorization process. Moreover, few reports have considered the reaction area in the torpedo car in detail. In this study, the behavior of iron oxide reduction and effects of the iron oxide feeding rate and hot metal temperature on the dephosphorization rate were investigated in laboratory experiments and industrial plant tests in order to clarify the reaction area in the torpedo car, with the aim of increasing the dephosphorization rate by iron oxide.

2. Experimental Procedure

2.1. Laboratory Experiments

The effect of the hot metal temperature on the dephosphorization rate was investigated using a small-scale induction furnace, as shown in Fig. 1(a). Mechanical stirring was used to simulate the transitory reaction, which is the primary reaction site in the torpedo car, because it was difficult to simulate the reaction in the transitory reaction area in the flux injection method in small-scale experiments. The experimental conditions are shown in Table 1.

The hot metal temperature was held at 1573 K or 1623 K during the experiment. The initial composition of the hot metal was Fe–4.5%C–0.03%P. Changes in the phosphorous content in the metal were investigated by sampling the hot metal.

2.2. Industrial Plant Tests

Industrial plant tests were carried out at the hot metal pretreatment center at JFE Steel’s East Japan Works (Chiba District), as shown in Fig. 1(b). The experimental conditions are shown in Table 2. Dephosphorization flux (iron oxide and lime) was injected into the hot metal in the torpedo car with a carrier nitrogen gas under the condition of a constant hot metal temperature before flux injection. The flux feeding rate was varied in the range of 200 to 400 kg/min. The apparent reduction rate of iron oxide in the top slag was also investigated by nitrogen gas bubbling. Further, the immersion depth of the lance was varied from 500 to 1000 mm to evaluate the reaction site in the torpedo car. Metal and slag samples were taken at 5 min intervals to examine changes in the metal and slag composition.
3. Experimental Results

3.1. Laboratory Experiments

Figure 2 shows the change in the phosphorous content in the hot metal at 1 573 and 1 623 K. In terms of thermodynamics, the dephosphorization reaction becomes more active as the temperature decreases. However, the dephosphorization rate increased as the temperature increased. This is attributed to acceleration of the iron oxide reduction reaction at higher temperatures, as will be discussed in detail in Sec. 4.4.

3.2. Industrial Plant Tests

Figure 3 shows the effects of the flux feeding rate on the change in the phosphorous content in the metal and the iron oxide content in the slag. As the iron oxide feeding rate was increased, the dephosphorization rate increased, but the rate of increase in the dephosphorization rate decreased when the flux feeding rate exceeded 350 kg/min. In the torpedo car, iron oxide which had not reacted with metal components accumulated in the top slag. The accumulation rate of iron oxide in the top slag increased as the flux feeding rate increased. The effects of the lance immersion depth on changes in the phosphorous content in the metal and the iron oxide content in the slag are shown in Fig. 4. When the lance immersion depth was increased, the dephosphorization rate increased. The iron oxide accumulation rate decreased as the lance immersion depth was increased, but the rate of increase in accumulation decreased when the lance

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Table 1. Experimental conditions (Laboratory experiments).

| Metal | 15 kg |
|-------|-------|
| Flux  | Iron ore 160 g/ch |
| Hot metal temperature | 1623K 1573K |
| Initial composition of metal | [\%C] 4.5, [\%Si] - , [\%Mn] - , [\%P] 0.03 |
| Rotation of impeller | 800 rpm |

Table 2. Experimental conditions (Industrial plant tests).

| Metal | 300 - 350 t |
|-------|-------------|
| Flux  | Iron oxide 200-400 kg/min, Lime 100 kg/min |
| Hot metal temperature | 1653K |
| Initial composition of metal | [\%C] 4.5, [\%Si] 0.1-0.2, [\%Mn] 0.3, [\%P] 0.12-0.15 |
| Carrier gas | N₂ 3 Nm⁻³/min |

![Fig. 1. Experimental method (a) induction furnace (30 kg-scale), (b) industrial plant tests (350 t).](image1)

![Fig. 2. Changes of phosphorous content in hot metal during induction furnace experiments.](image2)

![Fig. 3. Changes of phosphorous content in metal and (FeO)⁺(Fe₂O₃) content in slag.](image3)
immersion depth exceeded 750 mm.

4. Discussion

4.1. Outline of Reaction Zone

The reduction behavior of iron oxide injected into hot metal was analyzed based on the experimental results. Figure 5 shows an outline of the model of the iron oxide reduction reaction. Iron oxide reduction behavior was divided into three regions, as follows.

1) Transitory reaction zone
2) Effective reaction zone in top slag
3) Dead zone in top slag

The transitory reaction zone is defined as the reaction zone in which the iron oxide is reduced in the hot metal while floating up to the surface of the metal. The effective reaction zone is defined as the reaction zone in which reduction of iron oxide occurs in the top slag. The dead zone is defined as the zone in which iron oxide is not reduced and accumulates.

Three parameters were introduced in order to estimate the amount of reduction in these reaction zones quantitatively.

\[ \gamma : \text{proportion of iron oxide reduction in transitory reaction zone} \]
\[ \beta : \text{weight ratio of flux which moved into effective reaction zone to flux which did not undergo reduction in transitory reaction zone} \]
\[ \alpha : \text{weight ratio of slag in effective reaction zone to total top slag} \]

The behavior of iron oxide reduction was considered as follows. Iron oxide injected into the hot metal was reduced in the transitory reaction zone by the ratio of \( \gamma \), while floating up to the surface of the metal. At the top slag, iron oxide which was not reduced in the transitory reaction zone moves to the effective reaction zone by the ratio \( \beta \). The remainder of the iron oxide moves to the dead zone, where it accumulates.

In this model, \( \alpha \) and \( \beta \) are parameters which are not influenced by the hot metal temperature, lance immersion depth, and flux feeding rate, as assumed in the following Sec. 4.2.1. However, there is a possibility that they may change as a result of changes in the slag condition (for example, viscosity of slag) or other factors. Therefore, \( \alpha \) and \( \beta \) are defined separately.

4.2. Iron Oxide Reduction Behavior

4.2.1. Estimation of Iron Oxide Reduction Ratio

The assumptions used in calculating the iron oxide reduction ratio were as follows:

(a) The reaction between the slag and metal occurs in the transitory reaction zone and effective reaction zone in the top slag.
(b) Reaction does not occur in the dead zone.
(c) \( \gamma \) is proportional to the lance immersion depth, hot metal temperature, and flux feeding rate, while \( \alpha \) and \( \beta \) are constant.
(d) All iron oxide in the slag is considered to be (FeO).
(e) The reduction rate of iron oxide is proportional to the iron oxide content in the slag.

The amount of reduction of iron oxide in the transitory reaction zone \( (W_{\text{FeO}})^{\text{t}} \) is expressed by Eq. (1).

\[
W_{\text{FeO}}^{\text{t}} = \gamma Q_{\text{flux}} \frac{(%\text{FeO})_{\text{flux}}}{100} \text{ ..................................(1)}
\]

Where, \( (%\text{FeO})_{\text{flux}} \) is the iron oxide content in the injected flux. Iron oxide which did not react in the transitory reaction zone moves to the effective reaction zone of the top slag and is reduced. The change in the mass of iron oxide per unit time is expressed by Eq. (2) by the material balance of iron oxide, when iron oxide content is expressed as \( 100W_{\text{FeO}}/\alpha W_{\text{slag}} \).
\[
\frac{dW_{\text{FeO}}}{dt} \left(\%\text{FeO}\right) = \beta(1-\gamma)Q_{\text{flux}} \left(\%\text{FeO}\right)_{\text{flux}} \frac{100}{100} - \frac{\alpha W_{\text{slag}} K_{\text{Fe}}}{100} \left(\%\text{FeO}\right)
\]

\[\text{K}_{\text{Fe}}\text{ is the apparent rate constant of iron oxide. Assuming that the changes in slag volume are negligible and can be regarded as constant, the iron oxide content is expressed by Eq. (3), by integrating Eq. (2).}
\]

\[
\left(\%\text{FeO}\right) = \left(\%\text{FeO}\right)_{\text{slag}} - \alpha W_{\text{slag}} K_{\text{Fe}} \left(\%\text{FeO}\right) \times \exp\left(-K_{\text{Fe}} t\right) + \frac{\beta(1-\gamma)Q_{\text{flux}} \left(\%\text{FeO}\right)_{\text{flux}}}{100} \cdot \frac{W_{\text{slag}} \cdot K_{\text{Fe}}}{\alpha} \cdot \left(\%\text{FeO}\right)
\]

The value of \(\beta(1-\gamma)/\alpha\) was determined from experimental measurements of the value of \(\text{FeO}\) at each lance immersion depth and the value of \(K_{\text{Fe}}(=0.045 \text{ (1/min)}) based on experimental results of N_2 gas bubbling in the torpedo car. The relationship between the value of \(\beta(1-\gamma)/\alpha\) and lance immersion depth is shown in Fig. 6. As the lance immersion depth was increased, the value of \(\beta(1-\gamma)/\alpha\) decreased. Thus, from the results in Figs. 4 and 6 and assumption (c), if the parameters \(\alpha, \beta, \gamma\) were separated and determined using Eqs. (3) and (5) with data for lance immersion depths of 1 000 mm and 500 mm. The amount of reduction of iron oxide in each reaction site and the mass of accumulation in the torpedo car could then be calculated. Figure 7 shows the calculation results for a flux feeding rate of 400 kg/min. The iron oxide injected into the hot metal was reduced by 61% in the transitory reaction zone and by 11% in the effective reaction zone in the top slag. The remaining 28% of the injected iron oxide was not reacted and accumulated in the dead zone in the torpedo car. The effects of the hot metal temperature and flux feeding rate on \(\gamma\) were also examined in detail.

4.2.2. Effect of Hot Metal Temperature on Reduction Rate of Iron Oxide in Transitory Reaction Zone

In transitory reaction zone, the change in the iron oxide content is expressed by Eq. (6) using the apparent reaction rate constant \(K_{\text{Fe}}\).

\[
-\frac{d\left(\%\text{FeO}\right)}{dt} = \left(\%\text{FeO}\right)_{\text{flux}} - \left(\%\text{FeO}\right) = K_{\text{Fe}} \left(\%\text{FeO}\right)
\]
If the mass of flux is constant across the reaction, Eq. (7) holds.

\[
\gamma = \frac{\%\text{FeO}_{\text{flux}} - \%\text{FeO}}{\%\text{FeO}_{\text{flux}}} \quad \text{(7)}
\]

Comparing Eqs. (6) and (7), it could be thought that \( \gamma \) is equivalent to \( K_{\text{Fe}} \); hence, the temperature dependence of \( K_{\text{Fe}} \) is considered to be equivalent to that of \( \gamma \). \( K_{\text{Fe}} \) is expressed by Eq. (8) using the mass transfer coefficient, reaction area, and volume of slag.

\[
K_{\text{Fe}} = \frac{A}{V} \cdot k = \frac{A}{V} \cdot \frac{D_{\text{O}}}{\delta} \quad \text{(8)}
\]

Where, \( D_{\text{O}} \) is the diffusion coefficient of oxygen in slag, and \( \delta \) is the thickness of the boundary layer. According to Eq. (8), the temperature dependence of \( K_{\text{Fe}} \) corresponds to that of the diffusion coefficient of oxygen in slag. Hence, the temperature dependence of \( \gamma \) is considered as that of \( D_{\text{O}} \). From this, it is considered appropriate that apparent activation energy should be obtained by the Arrhenius plot of \( \gamma \).

The relationship between the parameter \( \gamma \) and hot metal temperature \( T \) is shown in Fig. 8. \( \gamma \) decreased as the hot metal temperature decreased. Assuming the value of \( \ln \gamma \) is proportional to the reciprocal of the hot metal temperature, the apparent activation energy \( \Delta H \) (J/mol) can be determined from the slope. The temperature dependence (i.e., apparent activation energy) of the reduction rate of iron oxide in the transitory reaction zone was determined to be 132 kJ/mol. A regression function was obtained as Eq. (9) by using the least squares method for each plot in Fig. 6. In Eq. (9), \( \lambda_0 \) is a constant (=1.4×10^6). \( \eta \) is the function of flux feeding rate and will be discussed in Sec. 4.2.3. According to Eq. (9), for example, hot metal temperature is reduced from 1 653 to 1 563 K, the value of \( \gamma \) decreases by 40%.

\[
\gamma = \lambda_0 \cdot \eta \cdot \exp\left(-\frac{132 000}{RT}\right) \quad \text{(9)}
\]

Sasabe et al.\(^1\) reported the value of \( \Delta H \) as 196 kJ/mol based on measurements of the temperature dependence of the apparent diffusion coefficient of oxygen in CaO–SiO2–FeO slag. The value of \( \Delta H \) obtained in this study was somewhat lower than that in Sasabe et al. It was presumed that this difference in the value of \( \Delta H \) shows the influence of the slag composition.

4.2.3. Effect of Flux Feeding Rate on Reduction Rate of Iron Oxide in Transitory Reaction Zone

When the flux feeding rate is reduced to under 200 kg/min, all of the iron oxide in the flux injected into the hot metal is reacted in the transitory reaction zone. Therefore, \( \gamma \) is equal to 1.0. Substituting the experimental conditions and results in the first stage of treatment into Eq. (9), and assuming \( \eta \) is proportional to \( Q_{\text{flux}} \) in order to estimate the value of \( \eta \) at a certain flux feeding rate, Eq. (10) was obtained.

\[
\gamma = 1.19 \times 0.0010Q_{\text{flux}} \quad \text{(10)}
\]

According to Eq. (10), as the flux feeding rate is increased from 200 to 400 kg/min, the value of \( \gamma \) decreases by 20%.

4.2.4. Reduction Rate of Iron Oxide

The reduction rate of iron oxide in the transitory reaction zone in the flux per unit time \( Q_{\text{FeO}} \) is expressed by Eq. (11).

\[
Q_{\text{FeO}} = \frac{W_{\text{flux}}}{100} \times \left( \frac{d(\%\text{FeO})}{dt} \right) = \frac{W_{\text{flux}}}{100} \times K_{\text{Fe}}(\%\text{FeO}) \quad \text{(11)}
\]

Where,

\[
W_{\text{flux}} = Q_{\text{flux}} \cdot \Delta t \quad \text{(12)}
\]

Furthermore, it is considered that, when the lance immersion depth is changed from \( h_0 \) to \( h \), the value of \( \gamma \) is expressed as \( h/h_0 \). From this, by substituting Eqs. (7), (9), (10) and Eq. (12) into Eq. (11), the reduction rate of iron oxide in the transitory reaction zone is expressed by Eq. (13) on the basis of data for a lance immersion depth of 1000 mm (=\( h_0 \)).

\[
Q_{\text{FeO}} = \frac{Q_{\text{flux}}}{100} \times (1.19 - 0.0010Q_{\text{flux}}) \\
\times \lambda_0 \frac{h}{h_0} \exp\left(-\frac{132 000}{RT}\right)(\%\text{FeO})_{\text{flux}} \quad \text{(13)}
\]

In the case of top slag, it is considered that the iron oxide content which was not reacted in the transitory reaction zone and moved into the effective reaction zone in the top slag (\( \alpha W_{\text{slag}} \)) with ratio \( \beta \) accumulates and is reacted in the effective reaction zone. The temperature dependence of the reduction rate of iron oxide in the top slag was assumed to be the same as that in the transitory reaction zone. From this, the reduction rate of iron oxide in the top slag can be expressed by Eq. (14).

\[
Q_{\text{FeO}}^\beta = \frac{\alpha W_{\text{slag}}}{100} \times \lambda_0 \exp\left(-\frac{132 000}{RT}\right)(\%\text{FeO}) \quad \text{(14)}
\]

4.3. Analysis of Dephosphorization by Coupled Reaction Model

In this study, a coupled reaction model\(^6\) was applied to the analysis of dephosphorization behavior. The assump-
tions of the coupled reaction model are as follows.
(a) The reaction rate is determined by mass transfer in both the slag phase and the metal phase.
(b) The chemical reaction at the slag/metal interface is rapid and equilibrated at any time.
(c) The rate of CO gas evolution is evaluated by a phenomenological parameter, $G_{CO}$.
(d) The activity of oxygen at the slag/metal interface is common.

The reactions considered in this study are as follows.

\[ \text{[C]} + \text{[O]} = \text{CO (g)} \]...........................(15)
\[ \text{[Si]} + 2\text{[O]} = \text{(SiO_2)} \]...........................(16)
\[ \text{[Mn]} + \text{[O]} = \text{(MnO)} \]...........................(17)
\[ \text{[P]} + 2.5\text{[O]} = \text{(PO_{2.5})} \]...........................(18)
\[ \text{(FeO)} = \text{Fe} + \text{[O]} \]...........................(19)

The molar flux of the oxygen supply from the iron oxide in the transitory reaction zone is expressed by Eq. (20).

\[ J_{FeO} = \frac{Q_{FeO}}{M_{FeO} \lambda_{o}} = \left(1.19 - \frac{0.0010 \times Q_{flux} \lambda_{o} \times Q_{flux} h}{100 M_{FeO} \lambda_{o} \times \exp \left(-132000 \frac{RT}{h_{o}}\right)}\right) \%FeO \]....................(20)

Next, the molar flux of the oxygen supply from the iron oxide in the effective reaction zone in the top slag is expressed by Eq. (21).

\[ J_{FeO} = \frac{Q_{FeO} \theta}{M_{FeO} \lambda_{o}} = \frac{\theta W_{slag} \lambda_{o}}{100 M_{FeO} \lambda_{o} \times \exp \left(-132000 \frac{RT}{\theta h_{o}}\right)} \%FeO \]...........................(21)

The molar flux density of $\text{[Si]}$, $\text{[Mn]}$, $\text{[P]}$ in the metal is expressed by Eq. (22), and the decarburization rate is expressed by Eq. (23) using the above-mentioned phenomenological parameter $G_{CO}$.

\[ J_{X} = F_{X}([%X] - [\%X]* - F_{XO_{2}}([\%XO_{2}]* - ([\%XO_{2}])) \]...........................(22)
\[ J_{C} = F_{C}([\%C] - [\%C]* - G_{CO}(P_{CO}^{*}/P_{CO} - 1)) \]...........................(23)

Where, $X$ and $XO_{2}$ indicate $\text{Si}$, $\text{Mn}$, $\text{P}$, and $\text{SiO}_2$, $\text{MnO}$, $\text{PO}_{2.5}$, respectively. If each reaction occurs in a steady state, the mass balance of oxygen expressed by Eq. (24) is applicable.

\[ 2J_{Si} + J_{Mn} + 2.5J_{P} + J_{C} - J_{FeO} - J_{O} = 0 \]...........................(24)

The changes in each component in the metal in the transitory reaction zone can be calculated using Eqs. (20), (22), (23), and (24). In the effective reaction zone in the top slag, the changes in each component in the metal can be calculated using Eqs. (21), (22), (23) and (24). The total reacted mass can be calculated as the sum of the reacted mass in the transitory reaction zone and that in the effective reaction zone in the top slag. The temperature drop of the hot metal during dephosphorization treatment was calculated from the heat balance, considering the oxidation heat of C, Si, Mn, and P in the metal, the reduction heat of the iron oxide in the slag, sensible heat of the flux, and radiation heat loss. Typical data used in the model calculations are given in Table 3. The mass transfer coefficient in the metal was determined by substituting an estimated equation proposed by Kitamura et al.\(^8,9\) for the operating condition. Stirring energy was calculated by the equation proposed by Mori et al.\(^10\) The phenomenological parameter $G_{CO}$ was applied to the value given by Ohguchi et al.\(^6\). For parameters $\alpha$ and $\beta$, the average values obtained from the results of experiments in this study were used ($\alpha=0.36$, $\beta=0.40$). Figs. 9 and 10 show the results calculated from the model. The calculated results agreed with the actual data.
4.4. Effects of Hot Metal Temperature and Flux Feeding Rate on Dephosphorization Rate

In contrast to the conventional kinetic model proposed in the past, the model in this work considers the effect of the hot metal temperature and flux feeding rate on the oxygen supply rate from iron oxide. Figure 11 shows the temperature dependence of the iron oxide reduction ratio and dephosphorization rate. As the temperature decreases, both the iron oxide reduction ratio and the dephosphorization rate decrease. It is considered that the oxygen supply rate from the iron oxide is reduced as the hot metal temperature decreases, and as a result, the dephosphorization rate is also reduced, especially in the low phosphorous content region, being controlled by this phenomenon.

Figure 12 shows the relationship between the iron oxide reduction ratio, the dephosphorization rate, and the flux feeding rate. The iron oxide reduction ratio during treatment decreases as the flux feeding rate increases. This is presumably because the particles of flux (iron oxide and lime) injected into the hot metal cohere with each other in the hot metal, increasing the apparent diameter of these cohesive particles, which reduces the area of the slag/metal interface. However, as the flux feeding rate is increased, the amount of oxygen supplied per unit of time also increases, even though the iron oxide reduction ratio decreases. As a result, the dephosphorization rate increases as the flux feeding rate increases, but the rate of increase gradually decreases. For this reason, it is considered that oxygen utilization efficiency for dephosphorization is reduced when the flux feeding rate is increased.

5. Conclusion

In this study, the reduction behavior of iron oxide and the effects of the iron oxide feeding rate and hot metal temperature on the dephosphorization rate were investigated in laboratory experiments and industrial plant tests with the aim of increasing the dephosphorization rate. The results are summarized as follows:

(1) When the flux feeding rate was 400 kg/min, 61% of the iron oxide injected into the hot metal is reduced by a transitory reaction zone, while 11% is reduced by a permanent reaction in the effective reaction zone in the top slag. The remainder is not reduced and remains in the dead zone in the torpedo car in the form of iron oxide.

(2) The iron oxide reduction rate in the transitory reaction zone is dependent on the hot metal temperature and iron oxide feeding rate. When the hot metal temperature was reduced from 1 653 to 1 563 K, the iron oxide reduction rate decreased by 40%. The reduction ratio decreased by 20% when the iron oxide feeding rate was increased from 200 to 400 kg/min.

(3) From the results of calculations, it is considered that the oxygen supply rate from the iron oxide is reduced as the hot metal temperature decreases, and as a result, the dephosphorization rate is also reduced.

Nomenclature

- A: Geometrical area of slag/metal interface (m²)
- D₀: Diffusion coefficient of oxygen in slag (m²/s)
- G₃CO: Phenomenological rate constant of CO evolution (mol/m²/min)
- h: Lance immersion depth (mm)
- h₀: Base lance immersion depth (=1 000 mm)
- ΔH: Apparent activation energy of reduction of iron oxide (J/mol)
- Jₓ: Mole flux of component X (mol/m²/min)
- KₓE: Apparent rate constant of reduction of iron oxide (1/min)
- Fₓ: Modified mass transfer coefficient (=ρkₓ/100M)
- kₓ: Mass transfer coefficient (m/min) (x=m, s)
- M: Molecular weight (g/mol)
$Q_{\text{flux}}$: Flux feeding rate (kg/min)
$Q_{\text{FeO}}$: Reduction rate of iron oxide (kg/min)
$T$: Hot metal temperature (K)
$V$: Volume of slag or flux (m$^3$)
$W_{\text{slag}}$: Amount of slag (kg)
$W_x$: Mass of iron oxide reduced by [C], [Si], [Mn] and [P] (kg)
$\alpha$: Weight ratio of slag in effective reaction zone to total top slag ($-$)
$\beta$: Weight ratio of flux which moved into effective reaction zone to flux which did not undergo reduction in transitory reaction zone ($-$)
$\gamma$: Proportion of iron oxide reduction in transitory reaction zone ($-$)
$\delta$: Thickness of boundary layer (m)
$\eta$: Function of flux feeding rate ($-$)
$\lambda_0$: Constant ($=1.4 \times 10^4$)
$\rho$: Density (kg/m$^3$)

Superscripts
$t$: Transitory reaction zone
$p$: Top slag

Subscripts
$m$: Metal
$s$: Slag
$\ast$: Interface
$\text{flux}$: In flux

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