Behavior of Hot Metal and Slag in the Lower Part of a Blast Furnace and Its Application to Heat Indices

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Abstract

In high PCR operation, raceway shift to the wall side tends to increase peripheral gas flow and heat loss. Furthermore due to the increase of ore layer thickness, reduction retardation in the upper part of the ore layer becomes more obvious. This might be one of the causes of the increasing heat fluctuation. The low coke rate and high productivity operation limits its flexibility, and in such situation RAR adjustment by grasping the heat level of the lower part of the furnace precisely is critical. Therefore, we focused on the volume of the SiO(g) generation area, which was defined as a heat index based on a Si transfer mechanism. Its validity was then discussed. The influence of the PC origin ash, which causes heat fluctuation in high PCR operation, was also considered.

1. Introduction

In high PCR operation, raceway shift to the wall side tends to increase the peripheral gas flow and heat loss. Furthermore, due to increase in the thickness of ore layers, reduction retardation in the upper section of the ore layers becomes more obvious.¹⁾ This may contribute to increasing the heat fluctuation in the lower section of the furnace. Operation with a low coke rate and high productivity narrows the operational flexibility compared with that before, from the perspective of permeability and heat-flow ratio, and in such situation, RAR adjustment by grasping the heat level in the lower section of the furnace precisely is critical. Maintaining the heat level in the lower section of furnaces is one of the most important factors to continue stable operation. A representative index that expresses the heat level in the lower section of furnaces is hot metal temperature; however, the index does not always show the heat level in the high temperature region in the lower section of furnaces precisely. The temperature of the hot metal reaches its highest peak in the coke charge layer, which is a high-temperature region near the raceway, and then the heat is removed in the course from the blast furnace bottom to the main iron trough and near the skimmer (temperature sensing point). Therefore, if the heat removal amount varies, even when the hot metal temperature is adjusted to be constant, the temperature in the high-temperature region near the raceway may vary in some cases

Because of this, components (e.g., Si, Mn, and S) in hot metal

are also used as indices to determine the heat level. Previous studies used the ratio of the actual contents of these hot metal components to the equilibrium values as indices.^{2,3)} However, these indices cannot consider the influence of the productivity fundamentally. Although they are useful when the productivity is almost constant as indices that reflect furnace heat, such indices may not always show actual furnace conditions under conditions where the productivity significantly fluctuates, for example, in operation with an ultra-low productivity that originated from the bankruptcy of Lehman Brothers.

In addition, due to a large amount of PC injection, the blast furnace slag formation process may change. The coke rate is decreased in high PCR operation, so when the ash content in carbonaceous materials does not significantly change, the ash content originated in the coke decreases while that originated in the PC increases. The supply pattern of coke to a raceway (combustion field) is different from that of PC. Therefore, the ash released from the coke and the PC may behave differently. Ichida et al.⁴⁾ reported that slag composition distribution in the radial direction differs between near the raceway and on the deadman side in high PCR operation based on the sampling from commercial furnace tuyeres. Thus, in operation when heavy oil is injected, there is little change in the slag composition in the radial direction; however, in high PCR operation, the slag component is lower than the mean CaO/SiO₂ of the final slag in the region in the raceway while it has high CaO/SiO₂ in the region

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deeper than the raceway. This indicates that the ash originated in the PC does not shift to the deadman side much.

Considering the factors above, I studied the influence of ash originated in PC and furnace heat indices based on the Si transfer mechanism to achieve operation with a low coke rate (high PCR) and high productivity, focusing on the lower section of furnaces. This report presents the results.

2. Behavior of Ash Originated in PC

2.1 Influence of ash originated in PC

After high PCR operation starts, heat loads to the furnace bodies often increase. This increase is caused by a decreased heat-flow ratio and accelerated coke degradation due to the increased PCR. In addition to this, a phenomenon where a formed raceway shell prevents the gas flow toward the center of the furnace has been reported. Ariyama et al.⁵⁾ reported the relationship between the volatile matter/ash content of PC and the furnace wall temperature through off-line tests. The experimental results show that the higher the quantity of volatile matter, the more the raceway shifts toward the furnace wall side: When the ash content in PC exceeds 7%, a raceway shell is formed and even when the PCR and combustion focus are in equal levels, the furnace wall temperature in the upper section of the tuyere further increases.

However, as their experimental conditions, PC types for which the composition significantly varies were used and there was no slag dropping, so the differences in the calorific value of the PC and presence and absence of slag may have affected the formation of the raceway shell. Therefore, slag (3 to 15 mm) for which the composition had been pre-melted was charged with coke (9 to 13 mm) to perform raceway tests in this study.⁶⁾ As the test conditions, there was slag dropping, each of the final slag rate and slag composition was almost equal, and the coal was mixed such that the heat from partial combustion of PC to CO would be almost constant. Figure 1 illustrates an outline of the experimental apparatus. Tables 1 and 2 list the test conditions. Approximately four-hour combustion tests under base and low-ash content conditions were performed by injecting with a single lance. Figure 2 shows the mean deadman temperature one hour before the experiment end. The lower the ash



Fig. 1 Experimental apparatus of raceway test

content in the PC, the higher the deadman temperature. Regarding the temperature in the upper section of the tuyere, the thermocouple eroded under the base conditions during the experiment while it did not erode under the low-ash content conditions. Although quantitative discussion is impossible, when the ash content in the PC was low, the heat loads to the furnace body may have been lower.

After the experiments, the slag hold-up in each region ((1) to (3)in Fig. 1) was measured by disassembly sampling. The results shown in Fig. 3 show that in all regions, the lower the ash content in the PC, the smaller the slag hold-up. In addition, the analysis results show that the assimilation of the ash with the slag tends to concentrate near the raceway.

These results indicate that even if the final slag rate, slag composition, and calorific value were almost the same, when the ash content in PC was lower, the permeability deeper than the raceway was improved, which made it easier for the gas to flow toward the deadman side, which increased the temperature. As a result, the slag hold-up near the raceway may have been significantly decreased. 2.2 Measures against raceway shells

Coke burns while rotating in a raceway, so generated ash tends to spread in the furnace. PC is injected from the lance, so it may tend to be unevenly distributed and thereby a shell may be easily formed. Therefore, to continue stable high PCR operation, measures against raceway shells are required. As a means to eliminate formed shells, previous studies reported serpentinite⁷⁾ or converter slag^{8,9)} injection where basic substances are injected to decrease the viscosity and melting point of high-SiO₂ and high-Al₂O₂ slags forming

Table 1 Experimental conditions of raceway test

	PC ash [%]	Dripping slag			Final slag		
		SV	Al ₂ O ₃	C/S	SV	Al ₂ O ₃	C/S
		[kg/t]	[%]	[-]	[kg/t]	[%]	[-]
Base	8.6	270	11.8	1.42	297	15.1	1.28
Low ash	6.6	276	12.3	1.40	300	15.1	1.28

Table 2 Blast conditions of raceway test

Blast temperature	°C	1200
O2-enrichment	%	2.50
Blast humidity	g/Nm ³	30.0
PCI	g/Nm ³	152
Flame temperature	°C	2061







Fig. 3 Comparison of slag hold-up between different ash content in PC (① to ③ correspond to the location in the Fig. 1)

shells to improve the dripping property. Other studies have reported the usefulness of oxygen jet in which powder coke in shells is combusted by high flow oxygen to decrease slag hold-up¹⁰) and a co-axial lance of PC and oxygen.¹¹) To prevent shells from forming, general double lances may be effective and ash aggregation prevention by improving the dispersiveness using eccentric double lances has been reported.¹²

In addition, complex injection is expected to improve the quality of hot metal in addition to the elimination of shells. For example, a previous study has reported that in serpentinite injection, MgO is reduced and volatilized and Mg gas may contribute to the desulfurization reaction.⁷⁾

3. Process of Si Transfer to Hot Metal and Application to Heat Indices

3.1 Rate controlling process of Si transfer to hot metal

Although it is thermodynamically obvious that the Si content in hot metal has a positive correlation with the hot metal temperature, the pressure in a furnace and its productivity are also factors that affect the Si content in the hot metal. Even when the hot metal temperature is the same, the Si content in the hot metal changes depending on the operation timing and blast furnace. Therefore, although there are many reports on the Si transfer to hot metal, such as equilibrium, kinetics, and statistical analysis, none of these can always be universally applied. This may be because the rate controlling process of SiO(g) generation and absorption, described in a later section, varies depending on the operation conditions. The absolute value of the Si content in hot metal varies periodically and this is the influence of pressure, productivity, and other factors. The temperature dependence may differ because the reaction process itself that regulates the Si content in hot metal may be different.

The Si content in hot metal is originated in SiO_2 in coke, PC, and ore. Among these, the contribution of coke may be the largest since it tends to be high temperature and low-oxygen partial pressure that are SiO_2 reduction conditions. Regarding the reduction of SiO_2 , Tokuda et al.¹³ proposed the possibility that when the carbon absorption reaction into molten iron does not sufficiently proceed by the level of the tuyere and thereby fine molten iron particles drip

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through the slag layer because the FeO concentration in the slag on the hearth is low, the slag-metal reaction reduces SiO_2 ; they concluded that from thermodynamical consideration of the reaction involving SiO(g), the main Si transfer mechanism is the generation of SiO(g) from SiO_2 in coke with high SiO_2 activity and the reaction of the generated SiO(g) and iron containing carbon.

In addition, Tsuchiya et al.²⁾ reported that changes in the slag components during iron tapping over time show that S and MnO in the slag change over time, while changes in the concentration of SiO₂ are very small; thereby the Si transfer reaction by the slag-metal reaction does not play an important role. In actual fact, when oxygen partial pressure that is regulated by C-CO equilibrium or Fe-FeO equilibrium with FeO contained in hearth slag taken into account is used to calculate the equilibrium Si value of the slag-metal reaction, it does not necessarily agree with the Si content in hot metal for commercial blast furnaces.

Currently, it is considered that a reaction mechanism via SiO gas is the mainstream instead of the slag-metal reaction.^{2, 13–19} Thus, the reaction mechanism is the generation of SiO(g) according to Equation (1) and the absorption of SiO(g) according to Equation (2). The rate constant of such reaction via SiO(g) is larger than that of the slag-metal reaction and can describe the Si content in hot metal for commercial furnaces.

$$SiO_{2}(s, l) + C(s) = SiO(g) + CO(g)$$
(1)

$$SiO(g) + \underline{C} = \underline{Si} + CO(g)$$
(2)

However, which reaction regulates Si content in hot metal is not necessarily clear. Tsuchiya et al.¹⁵⁾ reported that SiO(g) absorption rate controlling regulates the Si content in hot metal. However, in their study, the SiO(g) partial pressure was evaluated at a high level of 10⁻² atm that was close to the equilibrium value. They considered that SiO(g) sufficiently exists in the SiO(g) absorption region and this might be a cause. In addition, Sugiyama et al.¹⁶ concluded that the SiO(g) absorption rate is significantly faster than the SiO(g) generation rate and thereby SiO(g) generation rate controlling regulates the Si content in hot metal. However, they assumed that the temperature of the hot metal around a raceway was equal to that of a solid. That means that they estimated the hot metal temperature as being high and thereby they may have valued the SiO(g) absorption rate as excessively fast. Therefore, I analyzed which reaction process regulates the Si content in hot metal for commercial furnaces. This section reports the results.

3.1.1 Quantitative expression of SiO(g) generation rate

SiO₂ sources are ash in coke and PC and gangue in ore. When considering the retention time at a high temperature and low-oxygen partial pressure, which are SiO₂ reduction conditions, and the area of the contact interface between SiO₂ and carbon, the contribution of coke may be the largest. One study has reported on the contribution of PC.²⁰⁾ However, in the case of PC, the retention time around a raceway, which is a high-temperature and low-oxygen partial pressure condition, is very short and thereby the influence on the Si content in hot metal may be limited from the perspective of kinetics. In addition, the aforementioned SiO₂ originated in ash in a raceway shell and gangue assimilates to slag around the raceway and its activity lowers. In addition to such, the area of the contact interface with carbonaceous materials is an order of magnitude smaller than that of SiO₂ in ash that is dispersed in the carbonaceous materials. Therefore, such SiO, cannot be considered a main generation source. Tsuchiya et al.²⁾ reported that the higher the ash content in coke, the higher the partition ratio of Si to metal. Therefore, transfer from SiO, in coke was considered in this study. Accordingly, analysis was performed based on generation rate Equations for SiO(g) from coke in this study. Yamagata et al. reported the following generation rate equations for SiO(g) from coke¹⁷⁾ (the coefficient was corrected due to conversion to the SI unit).

$$\begin{aligned} &\text{SiO}_2(s) + C(s) = \text{SiO}(g) + \text{CO}(g) & (3) \\ &\text{R}_1 = k_1 \cdot (C_{\text{SiO}2} - C_{\text{SiO}} \cdot C_{\text{CO}} / \text{m}_1) & (4) \\ &\text{k}_1 = 2.0 \times 10^4 \cdot \exp(-289\,000 / \text{RT}) & (5) \end{aligned}$$

Yamagata et al. also reported the influence of total pressure on the conversion reaction of SiO₂: As the total pressure is higher, the SiO(g) generation reaction is more suppressed, and the pressure dependence is almost zero at an atmospheric pressure of 3 atm or higher. In recent large blast furnaces, the atmospheric pressure around raceways is 3 atm or higher, so the second term originated in the pressure in Equation (4) was disregarded and only a forward reaction was considered in the analysis below.

$$R_1 = k_1 \cdot C_s$$

 $K_1 = K_1 \cdot C_{SiO_2}$ 3.1.2 Quantitative expression of SiO(g) absorption rate

Tsuchiya et al. reported the following equations for the rate of Si transfer to carbon saturated iron¹⁵) (the coefficient was corrected by the conversion to the SI unit).

$$SiO(g) + \underline{C} = \underline{Si} + CO(g)$$
(7)
$$d[\%Si]/dt = 10\kappa_{f} \cdot (A/M) \cdot P_{SiO}$$
(8)

(6)

Where, $\kappa_{\rm f}$ is the apparent rate constant. When it is mathematized based on the value reported by Tsuchiya et al., the following Equation (9) is obtained.

$$\log \kappa_{\rm f} = 6.54 - 12\,685/{\rm T} \tag{9}$$

In addition, the SiO partial pressure was calculated using the following equations as equilibrium partial pressure where the activity of SiO₂ (a_{SiO2}) in coke is 0.85 and the CO concentration in the bosh gas is determined as 35 vol%.

$$\begin{split} &\text{SiO}_2(\text{s}) + \text{C}(\text{s}) = \text{SiO}(\text{g}) + \text{CO}(\text{g}) & (10) \\ &\Delta \text{G}_{(10)}^{\circ} = 694126 + 26.997 \log \text{T} - 434.57 [\text{J/mol}]^{21} & (11) \\ &P_{\text{SiO}} = (\text{a}_{\text{SiO}_2} \cdot \text{a}_{\text{c}}) / P_{\text{CO}} \cdot \exp(-\Delta \text{G}_{(10)}^{\circ} / \text{RT}) & (12) \end{split}$$

3.1.3 Consideration of assumption for calculation

Because information to estimate correct conditions in a furnace is not sufficient at present, the following assumption is used for the temperature of SiO(g) generation and absorption regions and A/M.

Figure 4 shows the relationship between the Si content in hot metal and hot metal temperature at $T_{pig} + \alpha$ ($\alpha = 25$, 100)°C where it is assumed that the temperature difference between the hot metal temperature (T_{pig}) and temperature of the SiO(g) generation and absorption regions is constant in the case of SiO(g) generation rate controlling and absorption rate controlling. Although in such cases, the generation region volume and the hot metal retention time in the absorption region, which are parameters, vary depending on α , the figure shows that the relationship between the Si content in hot metal and hot metal temperature is mostly on the same curve. Therefore, the temperature dependence of the Si content in hot metal is hardly affected by the assumed α . Considering that SiO(g) generated in the high-temperature region around the raceway transfers to the dripping of hot metal in the upper section of the furnace, the temperature of the SiO(g) generation region and absorption region was assumed as T_{pig} +100°C and T_{pig} +25°C, respectively, in the following description. Then, the generation region volume and the retention time in the absorption region (parameters) vary depending on preconditions, so they are different from those in an actual furnace.

The A/M is assumed as follows, as the diameter of a liquid drop that can pass the clearances in the coke charge layer.

A/M=0.15 (equivalent to a sphere with a d	liameter of 6.2 mm)
$d_1 = (2\sqrt{3}-3)/3*d_s^{(22)}$	(13)
$d_s = 0.04 [m]$	

3.1.4 Example of SiO(g) generation rate controlling and absorption rate controlling

As the temperature dependence varies between SiO(g) generation rate controlling and absorption rate controlling, with the hot metal temperature plotted on the horizontal axis and the Si content in hot metal plotted on the vertical axis, the rate controlling process may be determined from the inclination.²³⁾ Figure 5 shows an example relationship for SiO(g) generation rate controlling and absorption rate controlling. The figure also shows the theoretical lines in the cases of the SiO(g) generation rate controlling and absorption rate controlling based on the methods described in 3.1.1 and 3.1.2. In Fig. 5(a), the inclination of the actual Si content in the hot metal against the hot metal temperature is almost in line with the theoretical line of the SiO(g) generation rate controlling. The inclination is clearly different from the theoretical line of the SiO(g) absorption rate controlling. For Fig. 5(b), on the contrary to the aforementioned case, the inclination of the actual Si content in the hot metal against the hot metal temperature is distributed almost in line with the theoretical line of the SiO(g) absorption rate controlling. In this report,



Fig. 4 Relation of hot metal temperature and Si content in case of SiO(g) generation/absorption rate controlling (calculated data)



Fig. 5 Relation of hot metal temperature and Si content in case of SiO(g) generation/absorption rate controlling (operation data)

the case in Fig. 5(a) is regarded as SiO(g) generation rate controlling and that in Fig. 5(b) is regarded as SiO(g) absorption rate controlling.

Daily mean data except data during shutdown is used to plot the relationship between the Si content in hot metal and hot metal temperature, and most results in recent high PCR operation are close to the inclination assuming SiO(g) generation rate controlling. The process that regulates the Si content in hot metal may be determined by the relative relationship between the SiO(g) generation rate and absorption rate. For example, Fig. 6 shows cases where the height of a cohesive zone is different. When the cohesive zone is at a high place, SiO(g) generated around the raceway is completely absorbed by dripping hot metal, so the process may be SiO(g) generation rate controlling where the SiO(g) generation rate regulates the Si content in hot metal. On the contrary, when the cohesive zone is located at a low position, the retention time for dripping hot metal is short and thereby not all the generated SiO(g) can be absorbed. In such a case, the process may be SiO(g) absorption rate controlling where the reaction rate of absorption of the SiO(g) into the hot metal regulates the Si content in the hot metal. Although the height of a cohesive zone was used as an explanation example here, the liquid permeability, etc. of a dripping zone also affects the hot metal retention time, so these can be factors that affect the rate controlling process.

In addition to the hot metal, it has been reported that SiO(g) is absorbed and reoxidized by other substances in actuality. Such influence has been incorporated into the parameters of the generation region volume and retention time in the absorption region in this study.

3.2 Application to heat indices²⁴⁾

3.2.1 SiO(g) generation region volume

The process is SiO(g) generation rate controlling in many cases, so the SiO(g) generation region volume (parameter) could be an index that shows the area of the high-temperature region around a raceway. On the assumption that all generated SiO(g) will transfer to hot metal, the SiO(g) generation region volume is calculated based on the data of hot metal temperature, [%Si], and productivity. The absolute value of the generation region varies depending on preconditions, so although they need to be closely considered, the relative relationship may almost stand.



Fig. 6 Example of inner furnace image in SiO(g) generation/absorption rate controlling

3.2.2 Calculated slag temperature

On the assumption that the reaction below is in equilibrium, the slag temperature is calculated from slag components focusing on the Mn-C-O slag-metal reaction on the hearth.

$$\underline{Mn} + CO(g) = MnO(s) + C(s)$$
(14)
The equilibrium relationship of the reaction above is as follows.
$$(a_{n-1} \cdot a_{n-1})/(a_{n-1} \cdot P_{n-1}) = \exp(-\Delta G_{n-1} \circ /RT)$$
(15)

Where,
$$\mathbf{a}_{MnO} = \gamma_{MnO} \cdot \mathbf{X}_{MnO} = \gamma_{MnO} \cdot \boldsymbol{\beta} \cdot (\% \text{MnO})$$

 $\mathbf{a}_{C} = 1$
 $\mathbf{a}_{L} = \mathbf{f}_{L} \cdot [\% \text{Mn}]$

When the relationship above is substituted and organized as follows. $(\%MnO)/[\%Mn]/P_{CO} = f_{Mn} \cdot exp(-\Delta G_{(14)}^{\circ}/RT)/(\gamma_{MnO} \cdot \beta)$ (16) $\log f_{Mn} = e_{Mn}^{C} \cdot [\%C] + e_{Mn}^{Si} \cdot [\%Si] + e_{Mn}^{Mn} \cdot [\%Mn] + e_{Mn}^{S} \cdot [\%S]$ (17)

Where, f_{Mn} is an activity coefficient of the Mn in the hot metal and a function of temperature and composition; however, within the variation range in actual operation, it can be regarded as a constant. The variable, β , is a coefficient to convert a molar fraction into mass% and this is also simply regarded as a constant. γ_{MnO} is also a function of temperature and composition.

 P_{co} at the interface between slag and metal is supposed to be CO



Fig. 7 Operational results after blown-in (Oita No.2 blast furnace)

generated at the interface due to smelting reduction. It should be given as static blast pressure + slag bath to be precise; however, it is difficult to gauge the accurate accumulated slag amount, so it is simply given as blast pressure. The slag temperature can be calculated from the slag and metal composition. Although the absolute value varies depending on preconditions, it can be regarded as an index that shows the heat level of the hearth.

3.2.3 Example of application to commercial furnaces

Figure 7 shows the changes in the various indices in the start-up operation after blown-in as an example. Although the hot metal temperature immediately after the blown-in is at a low level, the SiO(g) generation region volume and calculated slag temperature are very high. This shows that although the high-temperature region around the raceway is wide and the temperature of dripping materials is high in high RAR operation immediately after the blown-in, the temperature of the blast furnace hearth and runner has not sufficiently increased and thereby the heat removal amount from the hot metal is large. In addition, from the macroscopic perspective, the SiO(g) generation region volume and calculated slag temperature change in a similar way. As mentioned previously, different data was used for the SiO(g) generation region volume and calculated slag temperature and as the calculation method, the former is based on kinetics and the latter is based on equilibrium, so their calculation principles are completely different. Regardless of these facts, they change similarly, so they may be appropriate as indices that show the heat level in the lower section of a furnace.

A previous study has reported that the heat flux at a blast furnace hearth is related to both SiO(g) generation region volume and calculated slag temperature.²⁵⁾

4. Conclusion

To realize operation with a low coke rate (high PCR) and high productivity, the influence of ash originated in PC and furnace heat indices based on the Si transfer mechanism were studied focusing on the lower section of the furnace. The findings are listed below.

- 1) When the slag dripping and PC calorific value were almost constant, the increase in the ash originated in PC accelerated the peripheral gas flow under the single lance injection condition. To continue high PCR operation stably, measures to prevent raceway shells from being formed and to eliminate them are required.
- 2) I focused on the differences in the temperature dependence of the SiO(g) generation reaction and SiO(g) absorption reaction and estimated the rate controlling process based on the changes of the Si content in the hot metal against the hot metal temperature. As a result, the process was SiO(g) generation rate controlling in most cases in recent high PCR operation. Therefore, the SiO(g) generation region volume can be an index that shows the high-temperature region around a raceway.
- 3) Although the SiO(g) generation region volume and calculated slag temperature were based on different data and the calculation principle was completely different between them, they changed similarly. Therefore, they can be regarded as appropriate indices that show the heat level in the lower section of a furnace.

Symbols

- A: Area of the interface between the gas and molten iron $[m^2]$
- a: Activity of component i [-]
- C_{SiO2}: SiO₂ concentration [mol/m³]
- d: Diameter of the liquid drop [m]
- d: Diameter of the coke in the dripping zone [m]
- e^{*j*}: Interaction parameter [-]
- f_{Mn} : Activity coefficient of the Mn in the hot metal [-]
- k.: Reaction rate constant [s⁻¹]
- M: Molten iron weight [kg]
- P: Productivity $\left[t/(d \cdot m^3) \right]$
- P: Partial pressure of component i [atm]
- R: Gas constant $[J/(mol \cdot K)]$
- R_1 : Positive reaction rate [mol/(m³s)]
- T: Absolute temperature [K]
- T_{pig}: Hot metal temperature [°C]
- X: Molar fraction of component i [-]
- β : Coefficient when the molar fraction is converted into mass% [-]
- γ_i : Activity coefficient of component i [-]
- (%i): Concentration of component i in the slag [mass%]
- [%i]: Concentration of component i in the hot metal [mass%]

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