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# A process model for BOF process based on bath mixing degree

*Guang-hui Li*[1)], *Bao Wang*[1)], *Qing Liu*[1)], *Xin-zhong Tian*[1,2)], *Rong Zhu*[1)],
*Li-ning Hu*[2)], *and Guo-guang Cheng*[1)]

1) School of Metallurgical and Ecological Engineering, University of Science and Technology Beijing, Beijing 100083, China
2) Research and Development Center, Xingtai Steel Co. Ltd., Xingtai 054027, China
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**Abstract:** The process model for BOF process can be applied to predict the liquid steel composition and bath temperature during the whole steelmaking process. On the basis of the traditional three-stage decarburization theory, the concept of mixing degree was put forward, which was used to indicate the effect of oxygen jet on decarburization. Furthermore, a more practical process model for BOF steelmaking was developed by analyzing the effect of silicon, manganese, oxygen injection rate, oxygen lance height, and bath temperature on decarburization. Process verification and end-point verification for the process model have been carried out, and the verification results show that the prediction accuracy of carbon content reaches 82.6% (the range of carbon content at the end-point is less than 0.1wt%) and 85.7% (the range of carbon content at end-point is 0.1wt%-0.7wt%) when the absolute error is less than 0.02wt% and 0.05wt%, respectively.

**Keywords:** steelmaking; basic oxygen furnace (BOF); decarburization; modelling; prediction

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## 1. Introduction

Developed by researchers, most models for BOF control are the end-point control model, whose targets are the control of bath composition and temperature at the end-point [1]. With the development of metallurgical processes, process control for BOF has been receiving more and more attention. Carbon content and bath temperature control at the steelmaking end-point, raw materials consumption, splash, slag getting dry, and some other process problems are all influenced by process control. On the progress of detection techniques in steelmaking processes, the capability of acquiring process information is becoming stronger than before, which makes process control possible. In addition, a process model has become one of development trends in the field of mathematic models for BOF control. In China, most middle and small-sized converters have not installed dynamic detection equipment, and they mainly rely on the experience gained in operation, and the hit rate is lower at the steelmaking end-point. In the paper, a process model for these kinds of BOF was developed to improve the control accuracy at the steelmaking end-point.

The traditional three-stage decarburization theory for BOF is shown schematically in Fig. 1 [2], and this theory is widely accepted by metallurgical researchers and engineers. However, its practicability is limited because it does not reflect the specific effects of main factors on decarburization. In the steelmaking process, silicon content, manganese content, oxygen injection rate, bath temperature, and oxygen lance height are main factors that can influence decarburization [3-6], and this paper focused on the research on the effects of these factors on decarburization.

The three-stage decarburization theory can be expressed as follows.

The decarburization rate formula in the first stage:

Corresponding author: Qing Liu E-mail: qliu@ustb.edu.cn

$$-\frac{\mathrm{d}C_{[\mathrm{C}]}}{\mathrm{d}t}=kt \quad (1)$$

The decarburization rate formula in the second stage:

$$-\frac{\mathrm{d}C_{[\mathrm{C}]}}{\mathrm{d}t}=k \quad (2)$$

The decarburization rate formula in the final stage:

$$-\frac{\mathrm{d}C_{[\mathrm{C}]}}{\mathrm{d}t}=k(C_{[\mathrm{C}]}-C_{\mathrm{k}}) \quad (3)$$

where, $-\mathrm{d}C_{[\mathrm{C}]}/\mathrm{d}t$ is the decarburization rate, wt%·s$^{-1}$; $t$ the time, s; $C_{[\mathrm{C}]}$ the carbon content, wt%; $C_{\mathrm{k}}$ the lowest carbon content in bath, wt%; and $k$ the constant coefficient, which is different for each decarburization stage.

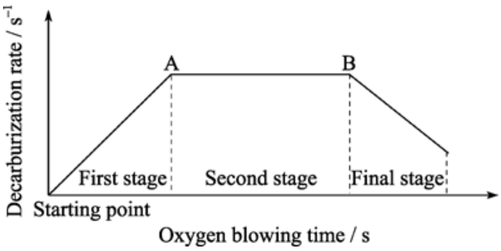


**Fig. 1. Traditional three-stage decarburization theory for BOF process.**

## 2. Establishment of the BOF process model

### 2.1. Effect of oxygen lance height on decarburization rate

In the steelmaking process, oxygen lance height has great effect on decarburization. The bath will maintain strong stirring if the oxygen lance height is lower, and the contact area between carbon and oxygen in hot metal is larger [7-8]. Therefore, the carbon content will decrease more quickly in this case. In this paper, the concept of bath mixing degree was put forward to describe the effect of oxygen jet on decarburization: bath mixing degree represented the stirring intensity and uniformity degree of oxygen jet on hot metal. The mixing degree expression is defined as

$$\eta=f(h) \quad (4)$$

where $\eta$ is the bath mixing degree, and its value is expressed in form of percentage, whose range is from 0 to 100%. The bath mixing degree is 0 when oxygen jet has no effect on hot metal, and the mixing degree is 100% when the effect is the strongest; $h$ is the oxygen lance height, m.

The relation between oxygen lance height and bath mixing time has been studied by Bao *et al*. [9-10]. They found that the longer the distance between the oxygen lance nozzle and hot metal surface is, the longer the mixing time is when the oxygen lance is at working position. According to their analysis results, the relation between bath mixing degree and oxygen lance height is summarized as linearity, so the concept of bath mixing degree is raised and can be defined as

$$\eta=\alpha(h_0-h) \quad (5)$$

where $\alpha$ is the constant coefficient, m$^{-1}$; $h_0$ the lowest position of oxygen lance when the bath mixing degree is 0, m; and the mixing degree is 0 when the oxygen lance height is more than $h_0$.

Eq. (5) describes the effect of oxygen lance height on bath mixing when the oxygen injection rate is invariable, and it can be applied to any converters when the oxygen lance is at working position. The bath mixing degree can be used to describe the area of decarburization reaction interfaces. During the BOF steelmaking process, oxygen participating in decarburization reaction relies on injecting gas continuously into molten steel by the oxygen lance; hence, the decarburization rate is also influenced by oxygen injection rate. The bath mixing degree and oxygen injection rate can be applied to improve the traditional three-stage decarburization model as follows.

(1) The first stage of decarburization can be expressed as

$$-\frac{\mathrm{d}C_{[\mathrm{C}]}}{\mathrm{d}t}=k_1 v\eta t \quad (6)$$

where $k_1$ is the constant coefficient of the first decarburization stage, wt%·m$^{-3}$; and $v$ the oxygen injection rate, m$^3$·s$^{-1}$.

(2) The second stage of decarburization can be expressed as

$$-\frac{\mathrm{d}C_{[\mathrm{C}]}}{\mathrm{d}t}=k_2 v\eta \quad (7)$$

where $k_2$ is the constant coefficient of the second decarburization stage, wt%·s·m$^{-3}$.

(3) The final stage of decarburization can be expressed as

$$-\frac{\mathrm{d}C_{[\mathrm{C}]}}{\mathrm{d}t} = k_3 v\eta(C_{[\mathrm{C}]} - C_{\mathrm{k}}) \tag{8}$$

where $k_3$ is the constant coefficient of the final decarburization stage, s·m$^{-3}$.

### 2.2. Effect of bath temperature on decarburization

In addition to carbon content and reaction interface area, decarburization rate is also influenced by bath temperature. The temperature can influence the constant coefficient of decarburization reaction; therefore, it is evident that the decarburization rate will be faster when the temperature increases.

Eq. (9) is deduced from the Arrhenius equation, and it reflects the relation between the constant coefficient of decarburization reaction and bath temperature:

$$k = \mu \mathrm{e}^{\omega/T} \tag{9}$$

where $\mu$ is the constant coefficient, which can be represented by $\mu_1$, $\mu_2$ and $\mu_3$, respectively, for the three-stage of decarburization; $T$ the bath temperature, K; and $\omega = -E/R$ (where $E$ is the reaction activity and $R$ the gas constant), the value of $\omega$ will not change for a particular reaction, $\mathrm{K}^{-1}$.

### 2.3. Discretization of decarburization process

Oxygen lance height and bath temperature have been dynamically varying during decarburization process, so it has a difficulty in determining the effects of oxygen lance height and bath temperature on decarburization directly. However, if the whole steelmaking process is divided into many time segments equally, the oxygen lance height and bath temperature can be approximately considered as unchanged values in every equal time segment when the time segment is short enough.

In this study, every decarburization stage is divided into $n$ time segments equally, that is, $t_0 - t_1$, $t_1 - t_2$, $\cdots$, $t_{n-1} - t_n$, where $n$ is different for each decarburization stage, $t_0$ is the initial time of decarburization stage, and $t_i$ is end moment of time segment $i$. Moreover, the corresponding oxygen lance heights in these time segments are $h_1$, $h_2$, $\cdots$, $h_n$, respectively, and the corresponding bath temperatures are $T_0$, $T_1$, $\cdots$, $T_{n-1}$, respectively.

In every equal time segment, the lance height and bath temperature at the initial time of the time segment are used to represent the lance height and the bath temperature of the whole time segment, respectively. Therefore, after the effects of oxygen lance height and bath temperature are considered on the basis of the traditional three-stage decarburization theory, the model of decarburization can be expressed as follows.

In the first decarburization stage,

$$C_{i-1} - C_i = \frac{\beta_1 v \mathrm{e}^{\omega/T_{i-1}}}{2}(h_0 - h_i)(t_i^{\,2} - t_{i-1}^{\,2}) \tag{10}$$

In the second decarburization stage,

$$C_{i-1} - C_i = \beta_2 v \mathrm{e}^{\omega/T_{i-1}}(h_0 - h_i)(t_i - t_{i-1}) \tag{11}$$

In the final decarburization stage,

$$\ln\frac{C_{i-1} - C_{\mathrm{k}}}{C_i - C_{\mathrm{k}}} = \beta_3 v \mathrm{e}^{\omega/T_{i-1}}(h_0 - h_1)(t_i - t_{i-1}) \tag{12}$$

where $\beta_1 = \alpha\mu_1/2$, $\beta_2 = \alpha\mu_2$, and $\beta_3 = \alpha\mu_3$.

As shown in Fig. 1, the decarburization rate is a continuous value during the whole steelmaking process, so the relation among $\beta_1$, $\beta_2$ and $\beta_3$ can be expressed as

$$2\beta_1 \Delta t_1 = \beta_2 = \beta_3(C_{\mathrm{B}} - C_{\mathrm{k}}) \tag{13}$$

where $C_{\mathrm{B}}$ is the carbon content of point B in Fig. 1.

For every equal time segment, Eq. (14) can be obtained from bath heat balance in steelmaking process:

$$Q_{i-1} + Q_{\mathrm{abs}} + Q_{\mathrm{rel}} = Q_i \tag{14}$$

where $Q_i$ is the bath physical heat at time $t_i$, it includes heat of slag and hot metal, kJ; $Q_{\mathrm{abs}}$ is the bath heat absorbed during time segment $i$, mainly including chemical reaction emission heat, kJ; and $Q_{\mathrm{rel}}$ is the bath heat released during time segment $i$, mainly including the heat that absorbed by assistant materials and taken away by exhaust gas and thermal radiation, kJ.

For some time segments, if it is possible to judge which stage it belongs to, the quantity of decarburization in this time segment can be calculated by the corresponding decarburization equation; then, the bath temperature at end moment of the time segment can be calculated by the heat balance equation. Further, the results obtained by calculation can be used to calculate the quantity of decarburization in the next time segment, and the behavior of decarburization and temperature of the whole steelmaking process can be obtained by loop calculation as this principle.

### 2.4. Linkage between three-stage of decarburization

Eqs. (10)-(12) established in this paper can express the behavior of decarburization of each stage well, which cannot describe the linkage points between the three stages. Thus, only the three-stage linkage is determined, the decarburization model developed can be considered as an integrated model for BOF steelmaking process.

(1) The linkage between the first stage and the second stage of decarburization.

The main difference of decarburization conditions between the first stage and the second stage is that the contents of silicon and manganese in the first stage are higher, and they play an inhibition role in decarburization. The oxidation of silicon and manganese is a first-order reaction, so the desiliconization equation can be obtained just like decarburization equation derivation. On the basis of considering three factors (lance height, bath temperature, and oxygen injection rate), the desiliconization is expressed as

$$C'_{i-1} - C'_i = \beta' v \mathrm{e}^{\omega'/T_{i-1}} (h_0 - h_i)(t_i - t_{i-1}) \tag{15}$$

As the same principle, the manganese oxidation can be expressed as

$$C''_{i-1} - C''_i = \beta'' v \mathrm{e}^{\omega''/T_{i-1}} (h_0 - h_i)(t_i - t_{i-1}) \tag{16}$$

where the superscripts of ‘′’ and ‘″’ represent the parameters for silicon and manganese, respectively.

In the paper, the inhibition role of silicon and manganese on decarburization is defined as follows:

$$\lambda = \rho_{\mathrm{Si}} (C'_{i-1} - C'_{\mathrm{R}}) + \rho_{\mathrm{Mn}} (C''_{i-1} - C''_{\mathrm{R}}) \tag{17}$$

where $\lambda$ is the inhibition coefficient of silicon and manganese on decarburization, and $\lambda \le 1$; $C'_{\mathrm{R}}$ is the maximum silicon content when silicon has no inhibition role on decarburization, wt%; $C''_{\mathrm{R}}$ is the maximum manganese content when manganese has no inhibition on decarburization, wt%; $\rho_{\mathrm{Si}}$ represents inhibition coefficient of silicon on decarburization, when $C'_{i-1} < C'_{\mathrm{R}}$, $\rho_{\mathrm{Si}}$ is 0; $\rho_{\mathrm{Mn}}$ represents inhibition coefficient of manganese on decarburization, when $C''_{i-1} < C''_{\mathrm{R}}$, $\rho_{\mathrm{Mn}}$ is 0.

Similar to the research on the effect of bath temperature on decarburization, the contents of silicon and manganese at the initial time of time segment can be applied to represent the contents of silicon and manganese during the whole time segment, respectively. The relation between decarburization rate and time is considered as a linear relation in the traditional three-stage decarburization theory, but taking the effect of silicon and manganese on decarburization into account, the first stage of decarburization can be improved as follows:

$$\begin{aligned} C_{i-1} - C_i &= (1-\lambda)\beta_1 \mathrm{e}^{\omega/T_{i-1}} (h_0 - h_i)(t_i - t_{i-1}) \\ &= \left\{1 - \left[\rho_{\mathrm{Si}} (C'_{i-1} - C'_{\mathrm{R}}) + \rho_{\mathrm{Mn}} (C''_{i-1} - C''_{\mathrm{R}})\right]\right\} \\ &\beta_1 v \mathrm{e}^{\omega/T_{i-1}} (h_0 - h_i)(t_i - t_{i-1}) \end{aligned} \tag{18}$$

(2) The linkage between the second stage and the third stage of decarburization.

During the final stage of decarburization, the decarburization rate will be affected by carbon content because of the limitation of carbon diffusion rate. Point B in Fig. 1 is a point where the decarburization rate begins to be influenced by carbon content, which is the critical point between the second stage of decarburization and the final one. In this paper, the carbon content of point B is chosen as 0.3wt% proposed by Vensel *et al.* [11].

After the linkages between the three stages of decarburization are determined, an integrated process model for BOF steelmaking process has been established completely. The integrated calculation flow diagram of the process model is shown in Fig. 2.

## 3. Verification and discussion

### 3.1. Process model verification

An assistant program for BOF process control has been developed based on the BOF steelmaking process model established in the paper. The software is developed by the Graphical User Interfaces tool (GUI) illustrated in Matlab7.6, which can be used to predict the carbon content and bath temperature during the whole BOF steelmaking process. The main interface of the program is shown in Fig. 3.

To verify the process model, practical tests were carried out. 67 heats of actual data obtained from Xingtai Steel in China were used to determine the coefficients of the process model, and then, process verification and end-point verification for the process model were carried out by the other 30 heats of data. The aim of process verification was to verify whether the decarburization behavior described by the process model accords with actual behavior. In the produc-

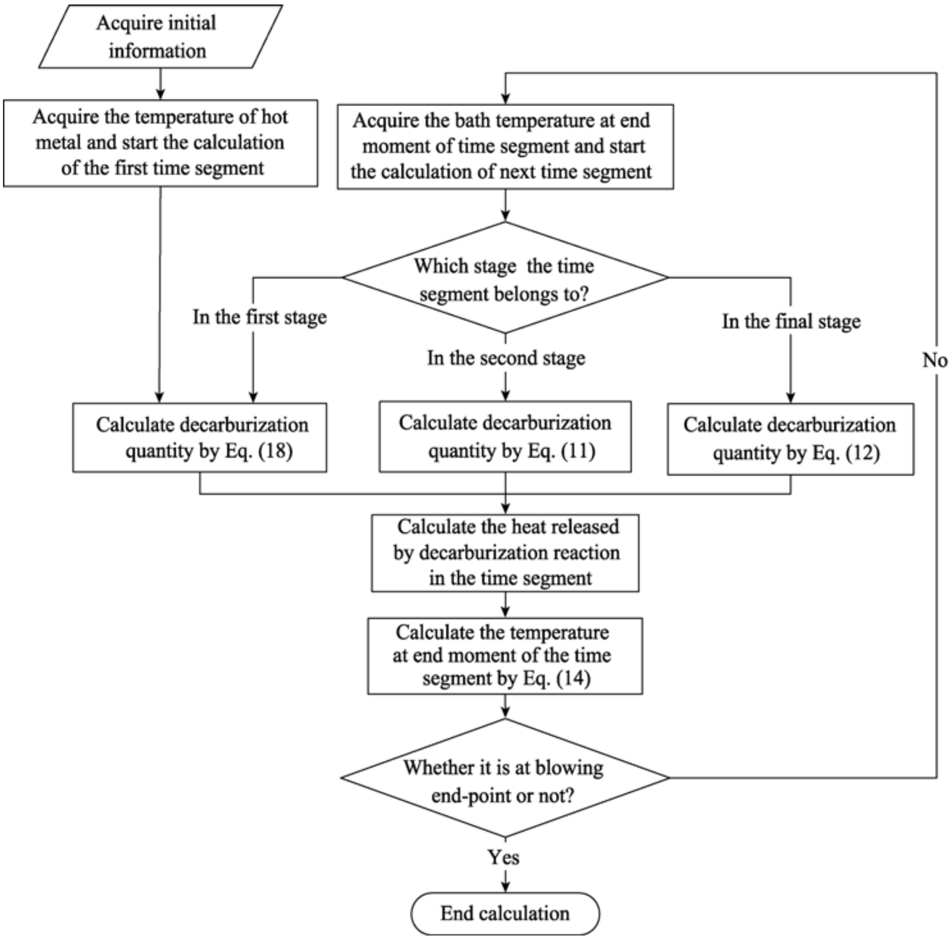


**Fig. 2. Calculation flow chart of the model for BOF steelmaking process.**

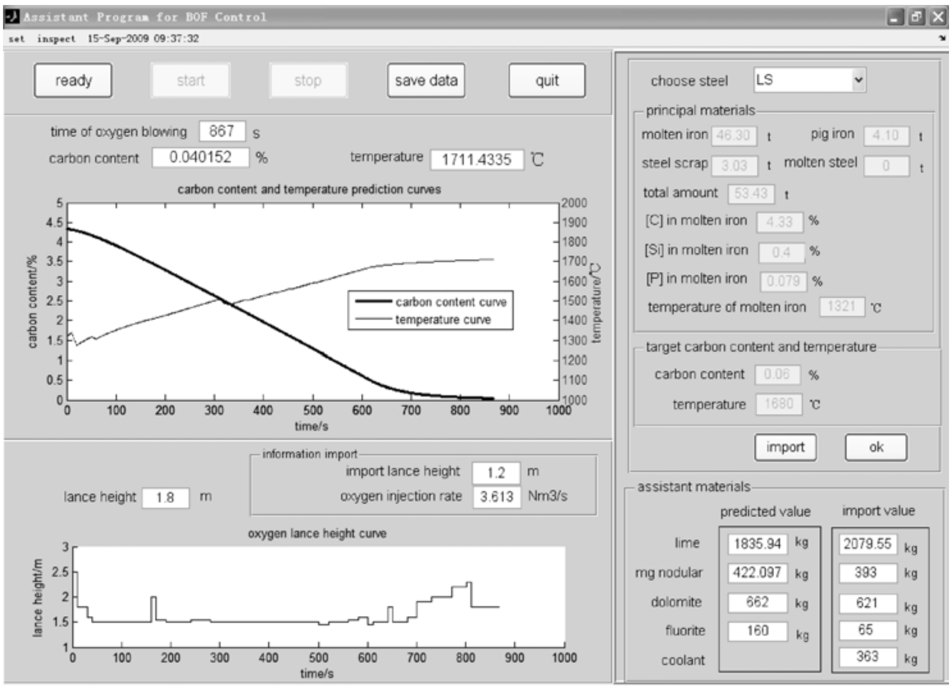


**Fig. 3. Main interface of the assistant program for BOF process control.**

tion process, a steelmaking process (manufacturing heat number: 220908614) was selected, actual carbon content in three different time in this steelmaking process was acquired by sample inspection, and these values have been used to compare with the predicted carbon content. The result is shown in Fig. 4, and the absolute errors of carbon content are all less than 0.02wt% in the comparison. During the steelmaking process, the variation of CO content in exhaust gas can indirectly reflect the variation of decarburization rate. For a steelmaking process (manufacturing heat number: 220908897), CO content has been used to compare with the predicted decarburization rate. The result is shown in Fig. 5, and their variation shows relatively good agreement. Hence, the results of process verification indicate that the model established in the paper basically accords with the actual behavior of decarburization.

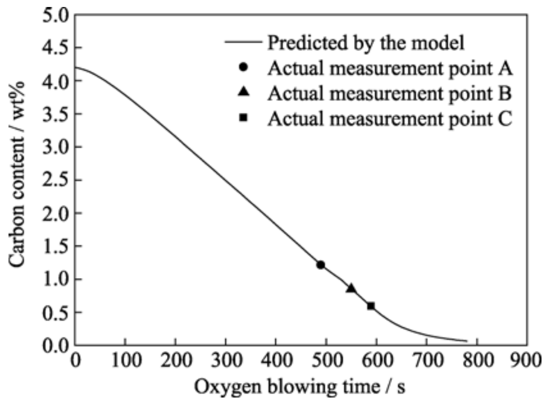


**Fig. 4. Comparison between predicted carbon content and actual measurement values (manufacturing heat number: 220908614).**

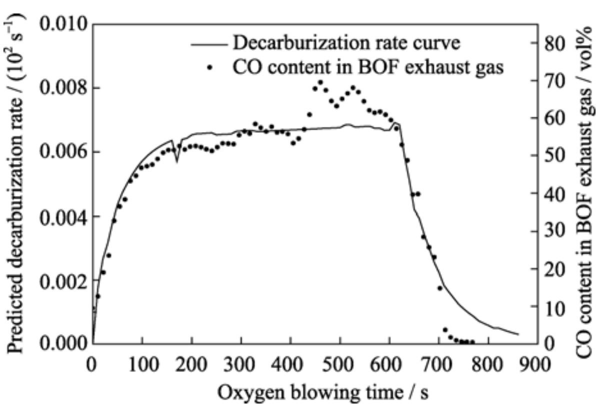


**Fig. 5. Comparison between predicted decarburization rate and CO content in BOF exhaust gas (manufacturing heat number: 220908897).**

The results of end-point verification are shown in Figs. 6-8, which can be summarized as follows: (1) the prediction accuracy of bath temperature at the end-point reaches 83.3% with the absolute error less than 20°C; (2) when the range of carbon content at the end-point is 0.1wt%-0.7wt%, the prediction accuracy of carbon content reaches 85.7%, while the absolute error is less than 0.05wt%, and the combined accuracy for carbon content and bath temperature reaches 71.4%; (3) when the carbon content at the end-point is less than 0.1wt%, the prediction accuracy of carbon content reaches 82.6%, while the absolute error is less than 0.02wt%, and the combined accuracy reaches 70.8%. Compared with other BOF end-point control models, it can be found that the process model above mentioned almost has the same level of accuracy with dynamic end-point control models [2, 12-21].

### 3.2. Discussion

A process model used to predict carbon content and bath temperature during steelmaking processes was established,

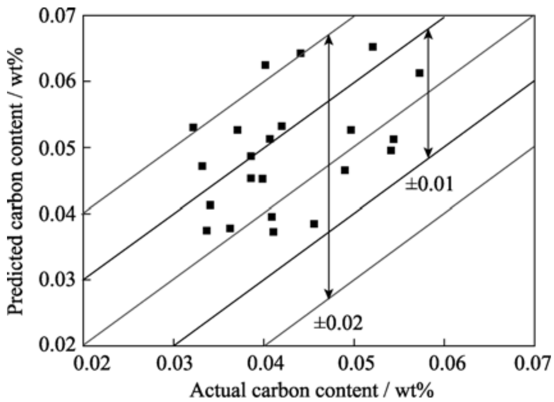


**Fig. 6. Prediction results of carbon content at the steelmaking end-point ([C]<0.1wt%).**

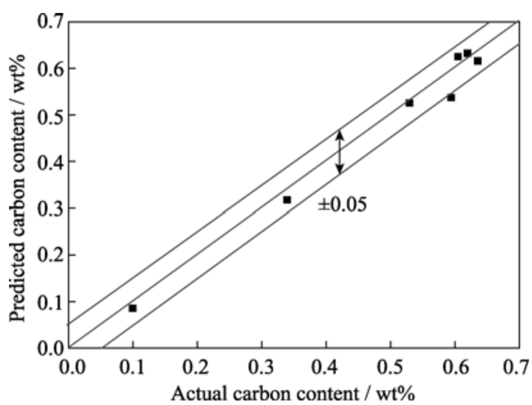


**Fig. 7. Prediction results of carbon content at the steelmaking end-point (0.1wt%<[C]<0.7wt%).**

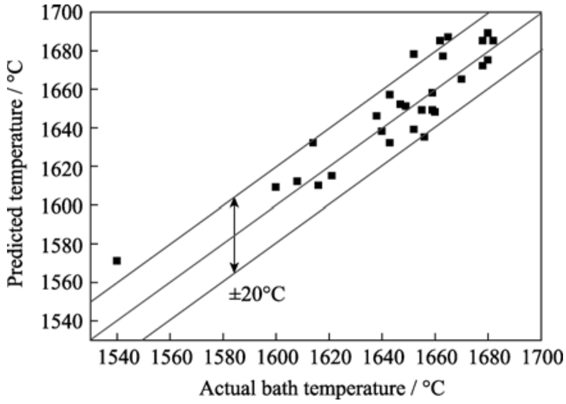


**Fig. 8. Prediction results of bath temperature at the steelmaking end-point.**

and the coefficients of the model were determined by a statistical regression method. If process dynamic detection equipment has been installed in BOF, the test results can be applied to modify the coefficients of the model, and it is significant to improve the accuracy of the process model. Thus, on this point, the model developed in the paper can be widely extended with some detection equipments.

Fig. 5 shows that the predicted decarburization rate changes smoothly in the second decarburization stage, but the CO content changes greatly in the stage, it is because iron oxides added into the bath as coolants are not taken into account, but have influence on decarburization. Moreover, the slagging process has not been considered when the model was derived; thus, the model accuracy is more or less influenced. However, the research of slagging can be carried out more easily based on the process model established in the paper, because the carbon content and bath temperature of steelmaking processes, which can be predicted by the process model, are very useful for the research on slagging. Meanwhile, the process model also can be improved on the basis of research on slagging process.

In this paper, although the study object is a top-blown converter, the process model can also be applied to a bottom-blown converter and a top and bottom combined blown converter after appropriate modification to the process model.

## 4. Conclusions

(1) The concept of bath mixing degree used to indicate the effect of oxygen jet on the decarburization has been put forward, and a new process model for BOF steelmaking processes has been developed based on the traditional three-stage decarburization theory.

(2) The results of process verification indicate that the model basically accords with actual decarburization behavior. The results of end-point verification show that the process model has relatively high prediction accuracy. Therefore, the process model established in the paper is available.

(3) The process model can predict the carbon content and bath temperature of the whole steelmaking process, so it can be used to optimize process operation and guide production practice.

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