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Continuous determination of bath carbon content on 150 t BOF by off-gas analyzer

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Abstract: The first imported off-gas analysis system on 150 t BOF at Benxi Plates Co. Ltd. is presented and the continuous determination of bath carbon content has been studied. The comparison between the whole-course carbon integral model and the end-point carbon prediction model has been made. The results show that the regular change of CO, CO_2 and N_2 content in the off-gas during blowing plays an important role in judging the smelting end-point of converter; the cubic curve fitting model has a higher hit rate over 95% for the heats whose end-point carbon content is lower than 0.10% with a precision of ±0.02% and has a large error for the heats whose end-point carbon content is more than 0.15%.

Key words: off-gas analysis; continuous determination of bath carbon; dynamic control; BOF

The continuous dynamic control model, based on on-line off-gas analysis of converter flue to get the real-time information, is a method different from the sublance end-point dynamic control model. This model can improve the hit rate and realize the whole-course dynamic control. As the primary choice, the mass spectrometer has been widely used in on-line off-gas analysis control on converter for its quick response, high precision and better adaptability in the hard steelmaking environment. Nowadays, many foreign steel companies have adopted various off-gas analysis dynamic models, for example, POSCO uses the Prima 600S segment mass spectrometer made in ONIX corp. in England, with a hit rate of end point over 95% and the hit rate of slopping prediction 81% [1]. There are also perfect performances in Japan Nippon Steel, US steel, Inland Steel, and SSAB plant in Lulea of Sweden and so on [2-4].

The first off-gas analysis system in China was imported from Danieli Corus to the Steel Works of Benxi Plates Co. Ltd. in June 2001. In this analysis system, the mass spectrometer is VG PRIMA δ, made in ONIX. The model development and testing of the continuous determination of bath carbon by off-gas analyzer was studied.

1 Off-gas analysis system

1.1 The off-gas analysis equipment

The off-gas analyzers are installed on three 150 t BOFs, including gas-sampling system, mass spectrometer and computer. The gas-sampling system consists of sample probes, gas-filtrating device (controlled by PLC) and transmitting pipelines. Main specifications of the BOF and gas analysis system are listed in **table 1**, and the specification of mass spectrometer is shown in **table 2**.

Table 1 Main specification of BOF and off-gas analysis system

Equipment	Number	Specifications
150 t BOF	3	The average time of blowing oxygen is 13 min, the oxygen flowrate is 30000 m^3/h, the average tap-to-tap is 41 min.
Gas analyzer	3	VG PRIMA δ mass spectrometer
Sample probes	3×2	Can be used under 1100°C and have the ability to prevent blockage by blowing in the opposite direction.
Gas-filtrating device	3	Controlled by PLC

Two gas-sampling probes are installed in the vertical position on the top of the converter flue, on the same side symmetrical in horizontal plane. The mass spectrometer and gas-filtrating device are installed in a small house on the flat roof near by the flue. The computer system with software system named Gas Work for calibration and communication is placed in the computer control room in front of the converter.

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The flow meter is installed on the horizontal pipe of OG (oxygen converter gas recover) system to measure the off-gas flowrate. **Figure 1** is the schematic arrangement of the off-gas analysis system.

Table 2 Main specification of mass spectrometer

Item	Specification
Mass spectrometer	Magnetic segment VG PRIMA δ made in ONIX
Analysis range	Gases, which atomic mass between 1 and 200, and volume fraction between 0 and 100%
Response time	Less than 0.3 s /per component
Accuracy	Relative error ≤0.1%

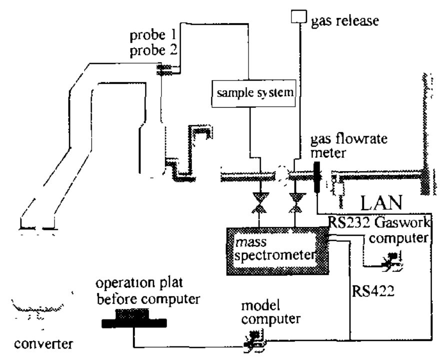

Figure 1 Schematic arrangement of off-gas analysis system.

The sample system uses two sample probes in turn; and it can automatically switch from one to the other by pressure sensor. The blocked probe can be open automatically by high-pressure impulse nitrogen gas and remains in idle state. The sample gas is passed to the gas filtration by pipes covered with heating lines, and then sent to the mass spectrometer after dedusting and filtering. The mass spectrometer sends the results to the computer.

1.2 Data collection and transmission

The mass spectrometer is connected with computer by RS232 or RS422 interface. According to the demand of user, it is easy to set the gases to be analyzed by the software Gas Work; these gases are mainly CO, CO_2, O_2, N_2, H_2, Ar, CH_4 and He for BOF control. The mass spectrometer can continuously analyze the gas content rapidly and accurately according to the designed period and set parameters after calibration by standard gases.

The period of data sampling is set to 3 s and the gases to be analyzed are CO, CO_2, O_2, N_2, H_2 and Ar on the 150 t BOF at Benxi Steel according to the capability of the mass spectrometer and the practical requirement of BOF operation; the data communication is carried out by RS422 interface. The real-time gas analysis data are displayed on the computer interface in the operation room to direct the operation.

2 Carbon prediction model by off-gas analysis

2.1 The whole-course carbon integral dynamic model

The carbon integral dynamic model is based on mass balance. The residual carbon in steel is calculated from the difference between the initial carbon input from the row materials and output in the form of CO and CO_2 in off-gas. The change trend of the carbon content in the bath is dynamically calculated by the model with continuous integration.

The d*c*/d*t* is calculated from carbon balance as expressed with CO and CO_2 content measured by the mass spectrometer and the off-gas flowrate measured by the flow meter.

$$dc/dt = 12/22.4 \cdot Q_{\text{off-gas}} \cdot [\varphi(CO) + \varphi(CO_2)] \quad (1)$$

where d*c*/d*t* is the decarburization speed of the bath, kg/s; $Q_{\text{off-gas}}$ the off-gas flowrate, m^3/s; φ(CO) and $\varphi(CO_2)$ are the volume fractions of CO and CO_2 in the off-gas.

The carbon content (mass fraction) in the melting bath is expressed by:

$$C(t) = (C_{\text{ini}} - \int_0^t (dc/dt)dt)/W_{\text{steel}} \quad (2)$$

where $C(t)$ is the carbon content in the bath at time t; C_{ini} the initial total carbon mass, kg; W_{steel} the mass of liquid steel, kg.

2.2 The carbon prediction model by curve fitting at the end point

This model is similar to the sublance model, just used in the later blowing time. The premise of the model is the decarburization speed which is related to the carbon content in the bath. The carbon content is predicted by this relationship.

(1) The carbon prediction model by exponential function at the end point.

The carbon prediction model by exponential function is one of the most popular models describing the decarburization characteristics in the later blowing time, its premise is that the decarburization speed has an exponential function relationship with the carbon content in the bath expressed by the following equation.

$$dc/dt = k_1(1 - e^{-k_2[C(t)-C_0]}) \quad (3)$$

Thus the carbon content in the bath is expressed by:

$$C(t)=C_0-\ln(1-dc/dt/k_1)/k_2 \quad (4)$$

where k_1, k_2 are the undetermined coefficients; C_0 the possible lowest carbon content in the bath.

Actually, the exponential model should be named logarithmic function as regard to the carbon content prediction.

The undetermined coefficients in equation (4) are solved iteratively by mathematic method from the decarburization speed calculated by equation (1) in the later blowing time.

(2) The carbon prediction model with other functions at the end point.

There are also some well-known curve functions for describing the decarburization characteristics in the later blowing time besides the exponential one.

(a) Quadratic function:

$$C(t)=b_0+b_1\cdot dc/dt+b_2\cdot(dc/dt)^2 \quad (5)$$

(b) Cubic function:

$$C(t)=b_0+b_1\cdot dc/dt+b_2\cdot(dc/dt)^2+b_3(dc/dt)^3 \quad (6)$$

(c) Inverse function:

$$C(t)=b_0+b_1/(dc/dt) \quad (7)$$

where b_0, b_1, b_2 are the undetermined coefficients.

3 Results and discussion

3.1 The off-gas analysis and the carbon prediction at the end point

N_2, CO and CO_2 contents in off-gas have regular change during the whole blowing period. It is useful for the carbon determination at the end point to identify and analyze the regularity accurately. In normal conditions, the variety of the off-gas content is gentle in the middle period, and near the end point CO drops dramatically but CO_2 and N_2 ascend. These typical off-gas characteristic curves in a heat are shown in **figure 2**.

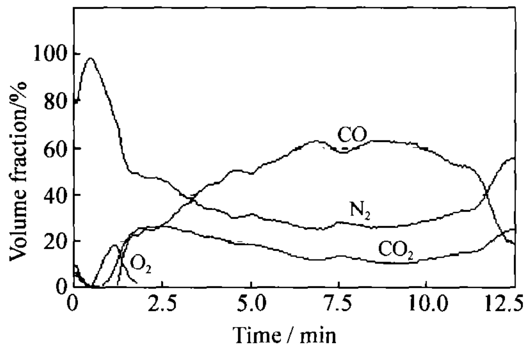

Figure 2 Characteristic curves of CO, CO_2, O_2 and N_2 contents in a heat.

From these curves, it can be found that several gas contents are often undulant near the end point, therefore, it is necessary to use one or more signals and carry through numerical value treatment for accurate carbon determination.

3.2 The decarburization speed and carbon determination at the end point

Although these gases analyzed by the mass spectrometer have a relationship with the carbon content at the end point, it is difficult to identify and calculate quantitatively because the gas content fluctuates near the end point. However, it is easier to predict the end-point carbon content from the decarburization speed calculated by the integral model, and it is also easy to calculate quantitatively.

Figure 3 is the decarburization speed. It can be found that an obvious degressive trend is appeared near the end point. Thus the carbon content can be determined with various numerical-fitting calculation from the curve.

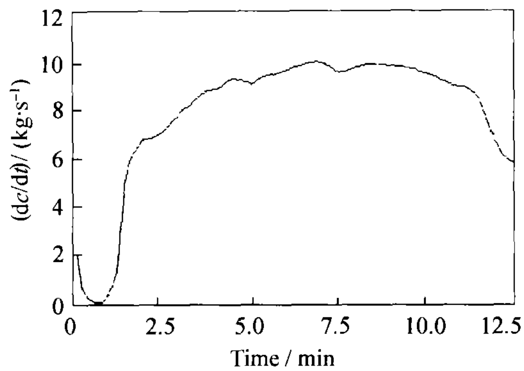

Figure 3 The decarburization speed calculated by integral model

3.3 The carbon integral model for the whole-course control in BOF

The change of carbon content in liquid steel calculated by the carbon integral model based on mass balance can be displayed on the monitor during the whole-course operation period. The precision of this model is related to the accuracy of input material weighting and the monitoring parameter measuring. The precision of carbon prediction by the model is dependent on the accuracy of the initial carbon content in the bath. It is essential to on-line continuously adjust the initial carbon content during blowing when the precision of the input material weighting is too poor.

Figure 4 is the carbon content calculated by the integral model during blowing. This can be shown on the computer monitor to control oxygen blowing.

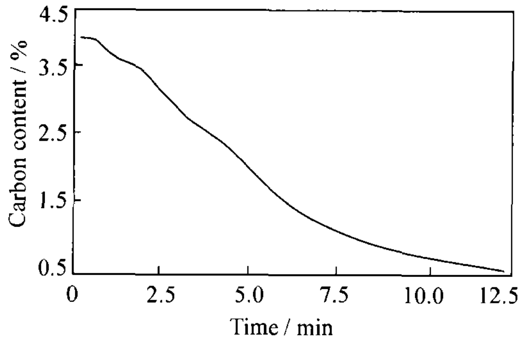

Figure 4 The carbon content (mass fraction) in liquid steel calculated by integral model during blowing.

3.4 The curve fitting model and the carbon determination at the end point

The theoretical basis of the curve fitting model is based on the assumption that the carbon content in liquid steel has a functional relationship with the decarburization speed in the later blowing time. In fact, the real carbon content in the bath just has a loose relationship with the decarburization speed as shown in **figure 5**. Although the decarburization speed does not have a linear relationship with the carbon content in all heats, it is sure that there is a direct relationship between them in this heat; and according to this assumption, the instantaneous carbon content in the bath can be calculated by continuously solving the undetermined coefficients in the equations during blowing.

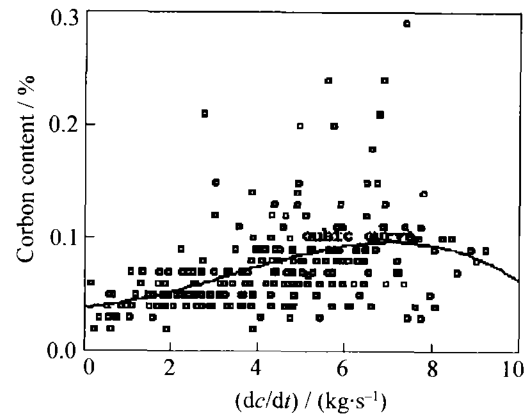

Figure 5 Scatter of the relationship between carbon content (mass fraction) and decarburization speed at end point.

The decarburization speed curve described by the familiar exponential equations is only approximate. There is tremendous difference between different heats. The results of curve fitting with four equations for 200 samples are listed in **table 3**. According to the results, the best curve is cubic, the second is quadratic, and the logarithmic curve next to them.

Figure 6 is the results predicted by the cubic model. Most samples' carbon content is less than 0.10%, which have high hit rate; however; the samples whose carbon content is more than 0.15% have low hit rate. The hit rate of carbon prediction by cubic model is above 95% with a precision of ±0.02% for the heats whose end-point carbon content is lower than 0.10%.

Table 3 Results of curve fitting with four kinds of equations

Items	Logarithmic	Quadratic	Cubic	Inverse
Multiple relativity	0.40027	0.42390	0.43119	0.24276
Standard error	0.03789	0.03753	0.03747	0.04011

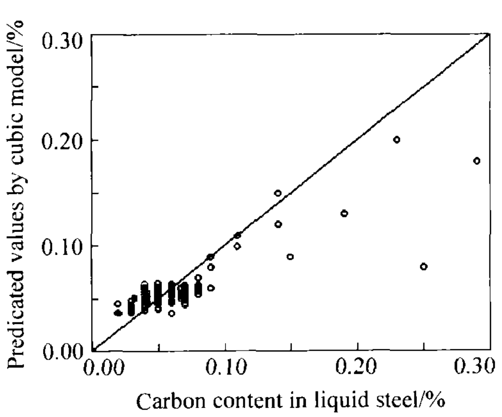

Figure 6 The prediction results of cubic model.

4 Conclusions

(1) CO, CO_2 and N_2 in off-gas are changed regularly during the whole blowing period, and identifying and analyzing these characteristics play an important role in the converter end-point determination.

(2) It is easier to predict the end-point carbon content according to the decarburization speed calculated by the integral model, and it is also easy to calculate quantitatively.

(3) According to the results of curve fitting and mathematical statistics analysis to four kinds of equations with 200 samples, the best model to describe the relationship between the end-point carbon content and the decarburization speed is cubic.

(4) The cubic model has a hit rate over 95% with a precision of ±0.02% for the heats whose end-point carbon content is lower than 0.10%.

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