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New Refining Control for LD Converter Using Independent Component Analysis†

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Abstract:

An LD converter is a widespread refining facility, which removes impurities from molten pig iron and adjusts the contents and temperature of hot metal to the requirements. JFE Steel developed new control algorithm for dephosphorization using an LD converter and evaluated the performance. The new control determines the control inputs based on Fe_tO transition in the slag estimated using the information of the exhaust gas, and the algorithm is composed of two main steps. The first step creates target Fe_tO transition in slag to lower the phosphorous content of the hot metal, applying independent component analysis to Fe_tO transition to extract the feature of the pattern. The second step determines the control inputs to form the Fe_tO pattern similar to the target based on the operation of the past heats. The new control was applied to an actual process and the result shows that the algorithm is effective to achieve low final phosphorous content of the hot metal.

1. Introduction

The converter, which is the key equipment in the blowing process, is used to remove impurities from the molten iron formed in the blast furnace and adjust the concentrations of carbon and alloying elements and the temperature of the hot metal. Continuous measurement of the condition of the hot metal in the converter during the blowing process is difficult because of the violent oxidation reaction which proceeds as a result of blowing oxygen into the converter. Moreover, since the object is a high temperature material, there are large errors in the values obtained by measurements, and even under the same operating conditions, there are significant differences in process behavior due to the effects of various unknown disturbances and variable factors other than measurement errors. These features made it difficult to construct highly accurate converter reaction models and to realize precise control systems utilizing such models[1)].

In this development, a converter dephosphorization control algorithm for determining control inputs by statistical use of past operational data was constructed, and its capabilities were verified by tests with an actual converter. The influence of measurement errors and unknown variations was reduced by statistical processing utilizing the new control algorithm, and satisfactory test results could be obtained. The new blowing control algorithm obtained in this development is expected to contribute to improved product quality, improved customer satisfaction and preservation of the global environment.

2. Dephosphorization by Converter Process

The object of this development is dephosphorization treatment by the converter. Dephosphorization is a pretreatment process in which the concentration of phosphorus in molten iron is reduced before decarburization in the converter. A stable reduction of the phosphorus in the hot metal after treatment is desirable. Performing dephosphorization in advance makes it possible to prevent over-oxidation of the molten steel and contamination of the molten steel by phosphorus-containing slag remaining in the converter in the decarburization process, which is performed with a different converter immediately after dephosphorization, and thus improves

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the cleanliness of the molten steel and the quality of final products. Dephosphorization also has the merit of reducing the total amount of slag formed by blowing[2].

The following explains the converter dephosphorization process using the schematic diagram of the converter equipment shown in **Fig. 1**. In converter dephosphorization, oxygen is blown into the converter from the converter top through a lance, and the phosphorus in the hot metal is oxidized and moves to the slag. The control inputs for blowing control include the pattern of the oxygen flow rate in blowing from the lance, the lance height pattern, the charging patterns of lime and other submaterials. These control input patterns are decided before blowing based on the composition of the hot metal, temperature information and other factors.

Equation (1) shows the dephosphorization reaction by Fe_tO in slag. Here, $t=1$; in other words, this is the case where FeO contributes to the dephosphorization reaction.

$$2[P]+5(FeO)=(P_2O_5)+5[Fe] \qquad (1)$$

In Eq. (1), square brackets [ ] mean components in the hot metal and parentheses ( ) mean components in the slag. As shown in this equation, the concentration of Fe_tO in the slag has a direct relationship with the dephosphorization reaction, and thus has a large influence on reaction progress. Therefore, use of this value in control can be expected to improve dephosphorization performance. Although it is difficult to measure the concentration of Fe_tO in the slag directly during operation, it is possible to calculate its trend from the mass balance of the various components which are input/output in the process. Concretely, by using measurement information including information on the hot metal before treatment (weight, composition), scrap charging information, submaterial charging information and exhaust gas information (flow rate, composition), the amounts of the components in the hot metal and slag can be estimated so that the masses of all components are in balance. The accuracy of the Fe_tO in the slag estimated by this calculation method was verified by analysis of slag samples, confirming that error is ±5% or less.

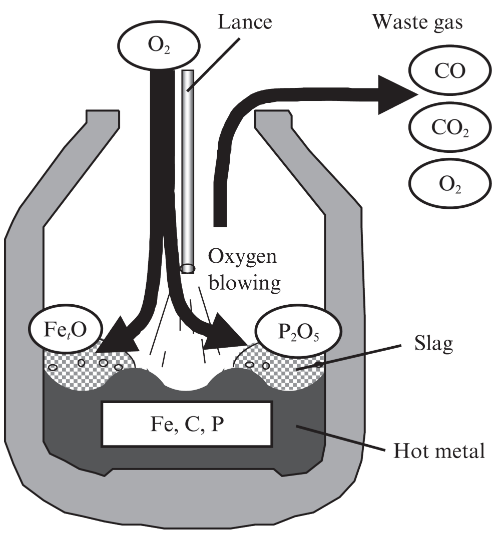

Fig. 1 LD converter and dephosphorization

3. Composition of New Control Algorithm

The control inputs which are the objects of this development are the oxygen flow rate and the lance height. The new control algorithm forms these patterns before the start of blowing. These two control inputs have the largest effects on the reaction in the converter and are important for adjustment of the concentration of Fe_tO in the slag. The concentration of Fe_tO in the slag has a large influence on the final hot metal phosphorus concentration after the end of dephosphorization treatment. Therefore, if a pattern of the Fe_tO concentration in slag which reduces the final phosphorus concentration can be obtained, there is a high possibility that the final phosphorus concentration after treatment can be controlled stably to a low value by determining the control inputs by targeting that pattern. Considering these points, a new control algorithm comprising the following two steps was constructed.

STEP1: Create the target transition of the Fe_tO concentration in the slag for the next heat based on the actual data from past heats.

STEP2: Determine the control inputs for the next heat based on the Fe_tO concentration in the slag and control inputs of the past heats and the target Fe_tO transition in the slag for the next heat.

In both steps, processing is performed utilizing actual past data in a statistical manner. The aim of this approach is to minimize deterioration of control accuracy due to measurement errors and unknown variable factors. The following explains the concrete content of the calculations in each step.

4. Method of Creating Target Fe_tO Transition in Slag (STEP1)

The transition of the Fe_tO concentration in the slag used in STEP1 changes depending on measurement errors and unknown variable factors. In order to reduce the influence of those factors, the authors considered a method in which feature component extraction of the transition of the Fe_tO concentration in slag is performed and a target transition is created based on the results of that calculation. The technique called independent component analysis (hereinafter, ICA) is used in the feature component extraction[3]. In this technique, calculations are performed in order to express multiple time-series signals as linear combinations of statistically independent time-series components. Concretely, the i-th time-series signal x_i is expressed as shown by Eq. (2).

$$x_i = w_{i,1}S_1 + w_{i,2}S_2 + w_{i,3}S_3 + \cdots + w_{i,m}S_m \quad \cdots\cdots\cdots\cdots (2)$$

Here, S_j shows independent time-series components, which form the same time-series as the respective time-series signals x_i. On the other hand, the coefficients $w_{i,j}$ by which components S_j are multiplied have values which differ for each times-series signal x_i. Because the time-series signals are expressed by a limited number of independent components S_j, a decrease in the influence of measurement error can be expected by application of ICA. A fast computational algorithm has already been proposed for calculation of numerical values for creating independent components and their coefficients. If that algorithm is used, easy implementation of a control algorithm which includes numerical calculations processing by ICA is possible. The new control algorithm calculates feature components and their coefficients by application of the fast computational algorithm using ICA to the transition of the Fe_tO concentration in slag in past heats (**Fig. 2**) .

The target transition of the Fe_tO concentration in slag differs depending on the condition of the hot metal before blowing and the treatment conditions, and it is difficult to express this feature by a process model. To reflect this influence, statistical treatment utilizing actual past data was incorporated in the computational algorithm which creates the target transition. **Figure 3** shows a schematic diagram of the algorithm which creates the target transition of the Fe_tO concentration in slag based on the concept outlined above. The steps in this process are summarized below.

STEP1-1: Apply ICA to the transition of the Fe_tO concentration in slag in past heats, and calculate the independent components S_j and their coefficients $w_{i,j}$.

STEP1-2: From the past heats, select all heats in which the final phosphorus concentration in the hot metal was lower than a reference value.

STEP1-3: For the selected past heats i, calculate the difference d_i of the values of the hot metal condition and treatment conditions in the past heats and in the next heat.

STEP1-4: Based on d_i, calculate the weights p_i for the past heats i.

STEP1-5: Calculate the weighted sum w_j^{next} for the independent component coefficient $w_{i,j}$ of the past heats by using p_i, and create the target transition of the Fe_tO concentration in slag x^{next} by using w_j^{next}.

The purpose in the above-mentioned STEP1-2 is to incorporate information on the transition of the Fe_tO concentration in slag in desirable heats by selecting heats with low final phosphorus concentrations. In STEP1-3, the differences between the values of the hot metal temperature, concentration of components and treatment conditions of the two heats are calculated, and the result of a calculation of the square root of the sum of squares of the weights is used as the difference d_i between the two heats. In STEP1-4, p_i is calculated as $p_i = \mathrm{f}(d_i)$ using the nonlinear function f. Here, f is a monotone decreasing function and has a value between 0 and 1. The setting of this weight p_i increases in past heats with smaller differences d_i. Finally, in STEP1-5, the coefficient w_j^{next} of the independent component S_j is calculated by using Eq. (3). Here, k past heats are selected in STEP1-2.

$$w_j^{\text{next}} = \frac{p_1 w_{1,j} + p_2 w_{2,j} + \cdots + p_k w_{k,j}}{p_1 + p_2 + \cdots + p_k} \quad \cdots\cdots\cdots\cdots (3)$$

w_j^{next} is a value which is close to the coefficient of a past

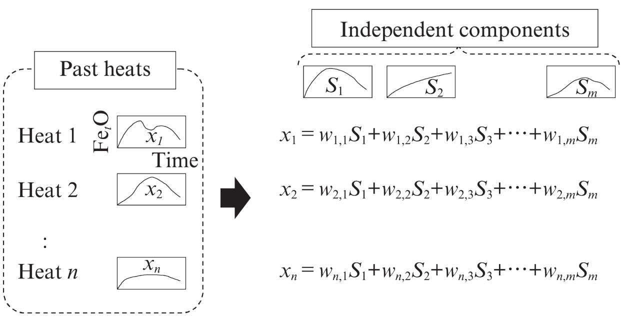

Fig. 2 Independent component analysis (ICA) of Fe_tO transition

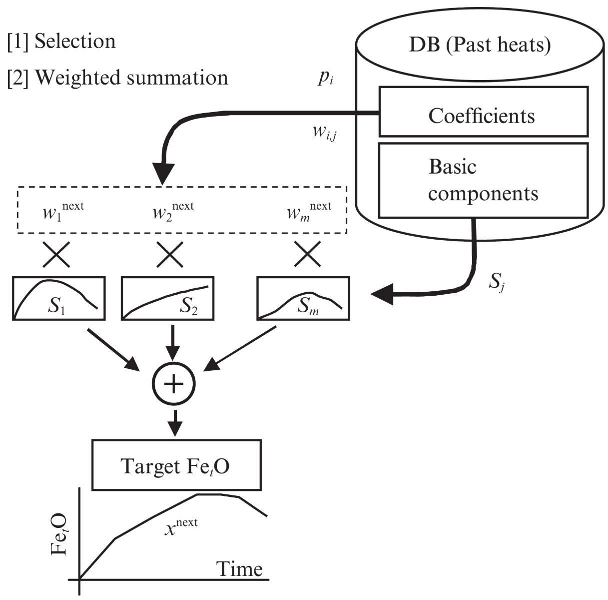

Fig. 3 Creation of target Fe_tO

heat in which the hot metal condition and treatment conditions are close to those of the next heat. Therefore, the calculation formula for the target transition of the Fe_tO concentration in slag x^{next} which is finally created is as shown in Eq. (4). x^{next} approaches the transition of the Fe_tO concentration in slag of a past heat which had a similar hot metal condition and operating conditions and a low final phosphorus concentration in the hot metal.

$$x^{next}=w_1{}^{next}S_1+w_2{}^{next}S_2+\cdots+w_m{}^{next}S_m \quad (4)$$

5. Determination of Control Patterns (STEP2)

STEP2 determines the control patterns for the oxygen flow rate and lance height so as to approach the target Fe_tO transition of the next heat. The purpose of this process is to achieve a stable low final phosphorus concentration in the hot metal by setting the control inputs by learning from past heats in which dephosphorization treatment proceeded favorably. **Figure 4** shows a schematic diagram of the algorithm for creation of control input patterns. The control inputs are determined by calculations in the proposed algorithm in accordance with the following steps.

STEP2-1: Collect the Fe_tO transitions x_i of past heat i selected in STEP1-2.

STEP2-2: Calculate the difference e_i with past heat i based on the difference between the Fe_tO transition x_i of the past heat and the target transition of the Fe_tO concentration in the next heat x^{next} and the difference of the operating conditions.

STEP2-3: Calculate the weight q_i of past heat i based on the difference e_i. (Calculated by the same method as in STEP1-4.)

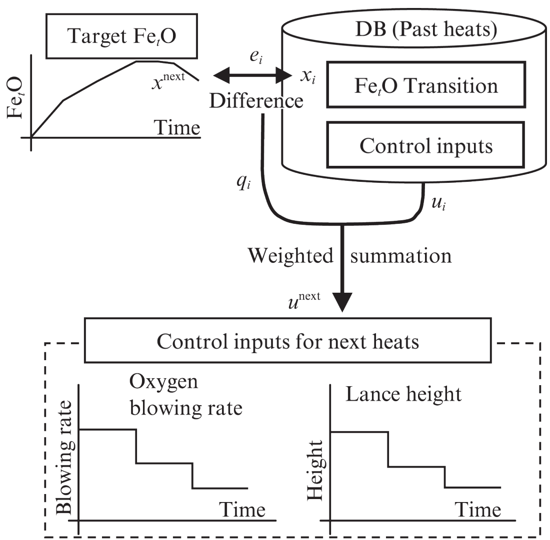

Fig. 4 Algorithm to determine control inputs

STEP2-4: Determine the control input u^{next} for the next heat by calculating the weighted linear sum for q_i of the control pattern u_i in past heat i.

In the above STEP2-2, the difference e_i is calculated by Eq. (5). Here, $x^{next}(t)$ and $x_i(t)$ denote the values of the t-th time-series x^{next} and t-th x_i.

$$e_i=\sqrt{\sum_t \left(x^{next}(t)-x_i(t)\right)^2} \quad (5)$$

The difference e_i becomes smaller in past heats in which the operating conditions are close to conditions under which the transition of the Fe_tO concentration approaches the target pattern. The weight q_i is set larger in the case of past heats in which the difference in STEP2-3 was smaller. Therefore, in STEP2-4, a pattern of a form which is close to the control pattern of past heats with a small difference e_i is easily created as the optimum control pattern. The calculation formula for u^{next} is shown in Eq. (6).

$$u^{next}=\frac{q_1u_1+q_2u_2+\cdots+q_ku_k}{q_1+q_2+\cdots+q_k} \quad (6)$$

It may be noted that the statistical treatment used in this control algorithm applies the same approach as the technique used in Just-In-Time modeling. In this technique, local models are created successively by using actual data; examples of various applications have been reported[4].

6. Experimental Results

The new control algorithm explained above was applied to an actual converter, and tests were conducted to verify its performance. **Table 1** shows the phosphorus concentration of the hot metal after treatment when using the conventional control method and the new control algorithm. With the conventional control method, the control inputs are determined by selecting one set of patterns corresponding to the operating conditions from among multiple oxygen flow rate and lance height patterns which were set in advance based on a metallurgical model. In Table 1, the values of the average and standard deviation of the phosphorus concentration in the hot metal after treatment when using the conventional control method are denoted by μ and σ, respectively. From these results, it can be understood that the phos-

Table 1 Phosphorous concentration of hot metal

	Number of heats	Phosphorous concentration	
		Average	Standard deviation
Conventional	467	μ	σ
Proposed	31	$0.863\,\mu$	$0.857\,\sigma$

phorus concentration in the hot metal after treatment has been successfully held to a low level with the proposed control algorithm in comparison with the conventional method.

Independent component analysis (ICA) and statistical treatment reflecting the hot metal condition and operating conditions are incorporated in the proposed control algorithm. It is considered that the influence of measurement errors and unknown variations, which had been problems in the converter blowing process, could be suppressed and satisfactory control results could be obtained effectively by using these features of the proposed control algorithm.

7. Conclusion

The paper introduced a new control technology for dephosphorization treatment using the converter and described its effectiveness based on the results of verification tests with an actual converter. The new control algorithm realizes improved performance by reducing the influence of measurement errors and unknown variable factors by introducing statistical techniques such as independent component analysis (ICA) for time-series information, in this case, the transition of the Fe_tO concentration in slag during dephosphorization. Improvement of the level of dephosphorization control performance makes it possible to improve the cleanliness of molten steel and supply higher quality products. Application of this technology realizes a shortening of blowing time and reductions in submaterial consumption and slag formation, thereby contributing to improvement of customer satisfaction by shortening delivery lead time and preservation of the global environment.

The details of this technology were published in the scientific journal, "Journal of Process Control." [5)]

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