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Research article

The chaotic characteristic of the carbon-monoxide utilization ratio in the blast furnace

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ABSTRACT

In this paper, carbon monoxide utilization ratio (CMUR) is served as a real-time index to evaluate the energy consumption of blast furnace (BF), and the chaotic analysis method is also presented to study the characteristic of CMUR. Firstly, the time series data measured from two representative BFs are adopted as the sample to investigate the characteristics of CMUR. Secondly, the phase space model of CMUR is reconstructed, and two key related parameters of the model are derived as well. Finally, the value of the chaotic attractor's saturated correlative dimensions in the reconstructed phase space of CMUR is obtained. The result shows that the sample time series of these two BFs have chaos property. Furthermore, the development process of CMUR is also proved to be the chaotic process. It provides a solid foundation for us to further study the chaotic predication and control of CMUR, which helps us to better master the variational tendency of CMUR and provides the effective operation guidance for the BF on the spot to reduce the energy consumption in BF.

1. Introduction

The energy utilization efficiency in blast furnace (BF) iron-making process is very important for energy-saving in the whole steel industry. To reduce BF's losses, a real-time energy consumption index (ECI) should be adopted, which can provide guidance to improve the production process in practical application.

Recently, some studies focused on the coke ratio (a kind of ECI) to enhance the energy utilization efficiency of BF, and achieved significant achievements in [1–3]. However, in the process of the BF's production, as to different production indexes or parameters, the sample interval of those data are not the same. For the coke ratio in the blast furnaces (BFs), due to the slow chemical reaction of coke, the sample interval of coke ratio usually takes 12 hours to 24 hours, which results in the long obtaining time. Thus, the coke ratio has the weak in real time operation, which may cause the optimizing and controlling lag in practical application. On the other hand, unlike coke ratio, as to the carbon monoxide utilization ratio (CMUR), due to the fast chemical reaction of *co* and co_2 in the BF, the variation tendency of CMUR becomes very speedy, and its sample time interval is 1minutes to 3minutes. Then, as a real-time parameter, compared with coke ratio, CMUR has the real-time advantage for monitoring and reflecting the BF's operating state. Furthermore, CMUR is the main factor influencing the energy consumption of BF, and it represents the operating state and energy consumption of BF. Moreover, it also can be obtained by analyzing the composition of top-gas in real-time. Therefore, CMUR can be used as real-time index to assess BF's energy consumption in this paper. However, due to the high complexity in practical production process, CMUR is difficult to understand and evaluate only by expert theory and experience for ordinary workers. Therefore, study the characteristic and variation tendency of BF's CMUR is significant for steel industry.

Considering it is difficult to analyze the correlation between CMUR with some other external key parameters (e.g., raw material composition, burden distribution matrix, blast temperature, gas injection, coal injection velocity, oxygen enrichment, etc.).

Up to now, various efforts have been made to overcome this deficiency. An investigation of Bell-less charging based on full scale model experiment to show that the burden distribution at the blast furnace top determines CMUR [4]. A connection between the CMUR and other parameters (e.g., raw material composition, burden distribution, top gas, etc.) was indicated by drawing the operating curve of BF [5]. In order to further analyze their connection, a compound calculation algorithm was proposed to obtain

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the CMUR mechanism mathematics model [6]. Moreover, numerical simulations on blast furnace operation with gas injection were performed by raceway mathematical modeling and exergy analysis, which corroborated that the gas injection had a strong influence on CMUR [7]. Besides, considering the gas pressure in BF, the correlation among the top gas pressure, blast pressure, blast volume and CMUR was analyzed, then a predicted model was presented to master the variational tendency of CMUR, which is put into the practice with a better result [8,9]. A correlation analysis between CMUR and other production efficiency indexes by combining mechanism of iron-making with actual production, then the result was applied to practice with a better guidance for practical operation [10].

Besides, it found that CMUR also changes along with the BF's working condition in practical cases. Some methods have been given to improve the BF's operation performance, so as to enhance CMUR. A comprehensive improvement strategy of CMUR was proposed to ensure the smooth BF operation, which including the optimization of raw materials, the enhancement of BF operation efficiency and the coordination of BF operation uniformity [11]. Based on expert theory and practical experience, a model of linear regression of CMUR was proposed and parameters in the model were optimized, which increased the value of CMUR successfully in the actual production [12].

However, the development trend of CMUR is not only influenced by the external factors, but determined by its own law. So, in order to know the law of CMUR so as the development trend of CMUR, it is of necessity and great significance for us to analyze the own characteristic of CMUR. Unfortunately, instead of its own characteristics, many former researches of CMUR focused more on the external factors and the mechanism model, but little attention has been payed on the characteristic analysis of CMUR. Therefore, the own property of CMUR should be further studied. In this paper, based some real data, we will validate the existence of chaotic characteristic of CMUR's development process, which is the foundation of prediction and control of the operating state and energy consumption in iron-making process.

Based on the above discussion, due to the advantage of real-time performance and the close connection with BF's energy consumption, the CMUR replaces coke ratio and it is used as a real-time ECI to assess BF's energy consumption in this paper. Besides, in the former studies of CMUR, the parameter analysis and mechanism model are usually studied in order to understand the variation tendency of CMUR. However, the intrinsic characteristic of CMUR is the main influence factor in the development process of CMUR, and few of former studies discussed it. Therefore, in this paper, a chaotic analysis method is presented to analyze the characteristic of CMUR.

This paper is organized as follows. First, some time series sample data of CMUR selected from two representative BFs are analyzed. Then, based on the phase space reconstruction technology, the reconstructed phase space of CMUR is introduced and the parameters, dimension and lag-time, are obtained by using the C-C algorithm and G-P algorithm successively. Finally, the existence and fractional characteristics of the saturated correlative dimension of CMUR's reconstructed phase space is deduced, which verifies the chaotic characteristic existence of CMUR in the BF.

2. CMUR's time series data analysis

2.1. CMUR's sample time series

The development process of CMUR is quite difficult to be mastered directly due to the high complexity of the BF, and only the time series data of the variables can be obtained in the BF. For the time series data of a variable, it not only contains all information of the process but also implicates its own development law.

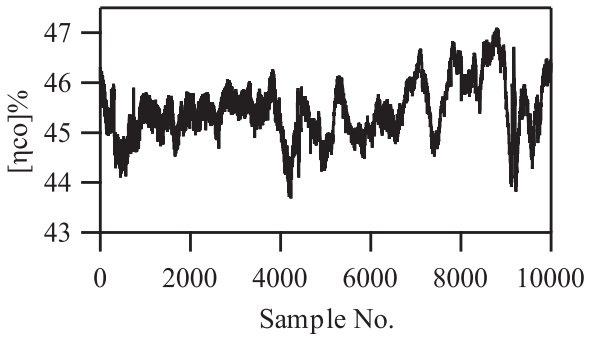

Fig. 1. [ηco] time series of 1100 m^3 BF at A iron and steel group Co.

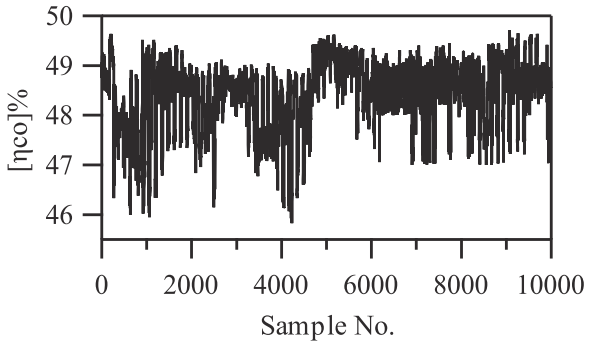

Fig. 2. [ηco] time series of 3200 m^3 BF at B iron and steel group Co.

In order to study the characteristics of CMUR and further understand its own development law in BF, Figs. 1 and 2 show the time series data of CMUR of two representative BFs (one is with the volume of 1100 m^3 BF, the other is 3200 m^3 BF) in different conditions are used as the example. There are 10^4 sample numbers in each data series, and the time interval is 3 minutes.

It can be seen from Figs. 1 and 2 that the CMUR (i.e., [ηco]) of company A mainly distributes in 0.43 and 0.47, while the one in company B distributes in 0.45 and 0.5. Additionally, for one BF, the CMUR still changes in every sample point because of the dynamic working condition of the BF.

The above characteristics are raised by the difference of volumes, circumstances, and furnace conditions of these two BFs.

2.2. The analysis of CMUR time series data

Due to the randomness and complexity of the CMUR's time series data, it is hard for us to extract the feature of the sample data only by observing them directly. Then, qualitative analysis (e.g., phase diagram method, power spectrum method, etc.) should be needed to analyze and recognize the time series preliminary.

The power spectrum is a method that can extract the feature of complicated time series' data. Besides, the time series acquired from the industrial working condition contain many noise components in BF, and the difference between them is inconspicuous. Considering the result of spectral characteristic is more accurate than other methods and it can distinguish the time series from the noise. So, to extract the feature or recognize the characteristic of the two sample noise time series better, the power spectrum analysis is employed in this paper firstly. According the technology of power spectrum [13,14], the analyses of power spectrum of the two series are shown in the Figs. 3 and 4 respectively.