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Soft-sensing method for slag-crust state of blast furnace based on two-dimensional decision fusion

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ABSTRACT

Slag crusts on the cooling stave of a blast furnace offer greatly protection for the furnace wall. Frequent forming and shedding of slag crusts (FSSCs) cause severe erosion on the wall, which affects the life of a blast furnace. However, it is very difficult to detect the FSSCs directly because of restrictions imposed by the structure of a blast furnace and detecting costs. This paper presents a soft-sensing method based on two-dimensional decision fusion to detect the state of slag crust (SSC) of a blast furnace. First, a soft-sensing scheme for SSC is put forward on the basis of features of slag crusts and the temperature detected in cooling stave. Next, methods for calculating a temperature threshold (TT) and a change-rate threshold of temperature (CRTT) are presented according to the characteristics of slag crusts. Finally, a two-dimensional decision method is presented by fusing the TT and CRTT to determine the SSC of the blast furnace. The experiment results based on industrial data demonstrate the effectiveness of the method.

1. Introduction

A blast furnace is an important reactor for ironmaking which consumes large amounts of resources and energy [1,2]. In an ironmaking process, solid burdens of ore and coke become molten state in the process of falling. Some of the molten burden sticks on the furnace wall and forms slag crusts on belly and bosh regions of the cooling stave of a blast furnace. Slag crusts form and shed under the effects of the edge-gas flow in the blast furnace and the cooling water in the stave. Frequent forming and shedding of the slag crusts (FSSCs), which produce a dramatic thermal shock on the cooling stave, directly affect the running state of the blast furnace and the lifetime of the cooling stave [3]. Stable slag crusts (the slag crusts do not form and shed frequently) protect the cooling stave, stabilize the edge-gas flow, and provide a good condition for ironmaking in the blast furnace [4]. Therefore, the state of slag crust (SSC), which is defined to describe the frequency of FSSC, is very important for ironmaking condition and lifetime of the blast furnace. However, it is very difficult to directly detect the SSC, because the inside environment in a blast furnace is extremely complex and harsh [5,6]. Therefore, in this study, a soft-sensing method was designed to accurately estimate the SSC of a blast furnace.

Since the slag crusts affect the temperature of the cooling stave, which is detected by the thermocouples installed in the cooling stave [7], SSC can be deduced by the change of the temperature. Many scholars have studied the influence of FSSC on the blast furnace based on the change of the temperature using one-dimensional, two-dimensional, or three-dimensional heat transfer mechanisms [8–10]. For example, based on one-dimensional heat transfer mechanism, a computational fluid dynamics (CFD) numerical simulation model of the cooling stave of a blast furnace was established to deduce the influence of FSSC on the blast furnace by analyzing the effects of the cooling stave material, the volume distribution of the cooling water pipes, and the nano-polymer in the cooling stave [11]. A three-dimensional temperature transfer mechanism of the cooling stave was analyzed to get the influence of FSSC on the blast furnace by analyzing the cooling capacity of the cooling stave at different flow rates of cooling water [12]. And an off-line cooling stave solid model was constructed to get the influence of FSSC on the blast furnace by simulating the cooling stave and slag crust heat transfer based on a finite element method [13].

For practical applications, the analysis methods for the influence of FSSC on the blast furnace based on the heat transfer mechanism are too complicated, the boundary conditions of the mechanism-based methods are too difficult to be determined, the

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actual structure and the heat transfer parameters are much different from the designed structure and parameters [14], and the theoretical heat transfer models are not sufficient to describe the actual unsteady heat transfer process. The above problems lead to the limitations of the mechanism-based methods to determine the influence of the FSSC on the blast furnace.

Since actual detected temperature data of the cooling stave in a blast furnace reflects the FSSC, data-drive methods have advantages to excavate the characteristics of the FSSC from the characteristics of data changes. Comparing with the mechanism-based methods, data-drive methods reduce the dependence of the empirical parameters, the heat transfer model, and the boundary conditions.

There are three main methods to excavate the change characteristics of the data: threshold-based methods, frequency domain-based methods, and template-based matching methods.

Threshold-based approaches are to find dividing point(s) of two types of data based on the inherent regulars of the data. A number of threshold-based methods have been devised in various areas, such as an near-threshold-based method for power-constrained and cost-sensitive health care-monitoring applications [15], a detection method based on a label propagation threshold for a highly efficient epidemic spreading model [16], and a sensitivity and specificity threshold-based method for diagnosing the amyotrophic lateral sclerosis [17]. These threshold-based methods extracted the inherent characteristics of the data signal, generally taking a fixed characteristic threshold to determine the classification. Although the FSSC have a significant effect on the temperature detected in the cooling stave, this effect is not fixed or linear. Therefore, if the FSSCs are directly identified by using one threshold, there is a one-size-fits-all problem, which leads to a large number of misjudgments.

Frequency domain-based methods refer to the analysis of a function or signal in its frequency-related part, which is used to describe the characteristics of the signal in the frequency function. Frequency domain-based methods are applied in many areas, such as a frequency-domain prediction model for extracting quasi-static phase features [18], a color filter array method based on its frequency-domain feature for measuring color component [19], and a thermoreflectance frequency domain-based method for measuring the contributions of broadband phonon [20]. The most basic requirement of the frequency domain-based method is that the detected data has its own unique frequency domain characteristics. However, the FSSC is affected by the operations, the distribution of burdens, and the parameters of the air supply system. These factors do not have regularity, which results in the randomness of the slag crusts. Therefore, the FSSCs do not have significant frequency-domain characteristics.

A template-based matching method is a technique in data processing for finding small parts of data which match a template pattern. A number of template-based matching methods have been devised in various areas, such as an acoustic template-based matching method for automatic emergency-state detection [21], a shape-based hierarchical part-template matching approach for human detection and segmentation [22], and a template-based matching method for a digital pulse processing algorithm of high-throughput spectroscopy [23]. The template-based matching methods require that the change of the data should have a significant shape (pattern) characteristic. However, in ironmaking processes, the intensity and the duration of the FSSCs are different, which leads to the lack of a significant shape characteristic of the data.

In summary, the calculation methods based on the heat-transfer mechanism are not applicable to industrial applications. The conventional signal separation methods are not fully adapted to detect the SSC because of the randomness and uncertainty of the FSSC. This paper presents a soft-sensing method based on two-dimensional decision fusion to detect the SSC of a blast furnace by excavating the characteristics of the FSSC.

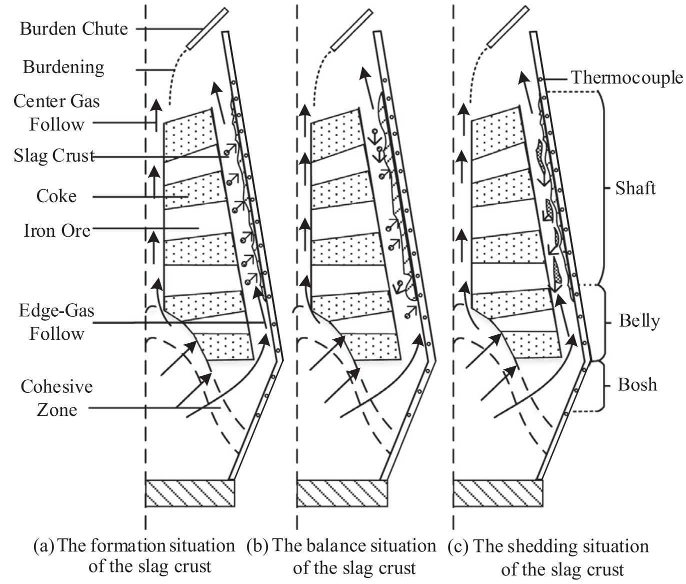

Fig. 1. The formation and shedding situation of slag crust.

The rest of this paper is organized as follows. Section 2 analyzes three situations of slag crust, the change characteristics of detected temperature, and the scheme of a soft-sensing method for SSC. The detail calculation of change-rate threshold of temperature (CRTT) and temperature threshold (TT), and a soft-sensing method based on two-dimensional decision fusion to detect the SSC of a blast furnace are presented in Section 3. Section 4 gives the verification results based on the actual industrial data. And, concluding remarks are summarized in Section 5.

2. Analysis of formation and shedding of slag crusts

In an ironmaking process, under the effect of the edge-gas flow in a blast furnace and along with the cooling effect of the cooling stave, slag crust forms and sheds. The formation and shedding of slag crusts are shown in Fig. 1.

The blast furnace edge-gas flow, which is produced by the reduction reaction that occurs between hot air and the burden layers (coke and ore layers) at the edge of the blast furnace bottom, flows rapidly along the edge of the blast furnace wall from the bottom to the top driven by the wind pressure of the blast furnace. The edge-gas flow erodes the slag crust on the furnace wall and the strength of the erosion depends on the amount of the edge-gas flow.

2.1. Three situations of slag crust

In the ironmaking process, some of molten burden sticks on the furnace wall and forms slag crusts under the effect of cooling water. When the edge-gas flow in blast furnace is strong and the mass of the slag crust is heavy, the slag crust sheds under the effect of the scouring of edge-gas flow and its own gravity. The slag crusts generally stay in the following three situations.

Formation situation: In this situation, the scouring effect of the gas flow is weak and the cooling strength of the cooling water plays a major role. The sticking molten burden becomes hard to form slag crusts on the belly and bosh of the furnace wall under the effect of the cooling water. Accordingly, the temperature detected by thermometers in the cooling stave reduces at this time.

Shedding situation: In this situation, the scouring effect of the gas flow plays a major role. The mass of the crust is heavy, the