Control Engineering Practice 78 (2018) 186–195

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

An energy efficient decision-making strategy of burden distribution for blast furnace

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ARTICLE INFO

Keywords:
Burden distribution
Blast furnace
Decision-making strategy
Support vector regression
Case-matching model

ABSTRACT

Burden distribution plays an important role in the optimization of energy-consuming index of a blast furnace (BF). However, due to the complex mechanism of the burden distribution process and the poor understanding of this process, it is difficult for operators to make a suitable decision for burden distribution parameters. In this paper, a decision-making strategy of burden distribution parameters is devised for improving energy-consuming index, where carbon-monoxide utilization rate (CMUR) is taken as the energy-consuming index. Firstly, the support vector regression is used to build a model between the burden distribution parameters and BF state variables that are closely related to CMUR. Then, a probability-based case-matching model is built by the historical data to predict the trend of CMUR's change. Finally, based on the trend of CMUR's change, a decision for burden distribution parameters is obtained. Simulation results based on industrial data show that the devised decision-making strategy provides a good guide on making a suitable decision for burden distribution parameters.

1. Introduction

A blast furnace (BF) is a complex metallurgical reactor that converts iron ore into liquid pig iron through a series of chemical and physical changes. Energy consumption is one of the most important factors in ironmaking, and is closely related to the state of the BF. Here the state is the combination of the variables that are used to describe the chemical and physical changes in the BF, and these variables include top temperature, permeability index, etc. A suitable distribution of gas flow in the BF creates a smooth state, and is fundamental for the reduction of energy consumption. In general, the distribution of gas flow is closely related to the burden distribution. Therefore, a correct decision of the burden distribution has great significance for the reduction of energy consumption.

In order to reduce the energy consumption in a BF, many researchers focused on building models to analyze energy consumption from the viewpoint of carbon efficiency. The proposed methods for reducing the energy consumption in a BF were mainly through adjusting the burden distribution or improving the properties of raw materials. For example, various types of iron ore were taken as the pre-reduced input materials to reduce the carbon dioxide emissions (Yilmaz & Turek, 2017). Carbon-monoxide utilization rate (CMUR) was often used as an energy-consuming index because it reflects the degree of energy exchange inside a BF and has real-time character suitable for monitoring the state of a BF. For example, a chaotic analysis method was presented to study the characteristics of CMUR (Xiao, An, He, & Wu, 2017). Watakabe, Takeda, Nishimura, Goto, Nishimura, Uchida, and Kiguchi (2006) used a high-ratio ore-mixed-coke charging technique to reduce the coke ratio.

For the decision-making of the burden distribution parameters, some researchers analyzed the burden distribution process and made a decision of burden distribution. A mathematical charging model was used to determine the best charging pattern according to the overall geometry stock line (Radhakrishnan & Ram, 2001). Kuang, Li, Yan, Qi, and Yu (2014) carried out a numerical study of multiphase flow, heat and mass transfer, showing that the hot charging improved the productivity and reduced the comprehensive coke ratio and carbon dioxide emission. Focusing on the nonuniform descending speed in the burden distribution process, a mathematical model for estimating the burden distribution was developed (Fu, Chen, & Zhou, 2015). Zhou, Li, Shi, and Zhou (2016) proposed a two-dimensional temperature distribution model to analyze the burden distribution process. Wu, Kou, Xu, Guo, Du, Shen, and Sun (2013); Yu and Saxén (2010) used a discrete

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https://doi.org/10.1016/j.conengprac.2018.06.019
Received 3 January 2018; Received in revised form 23 April 2018; Accepted 27 June 2018

Abbreviations

BF	Blast furnace
CMUR	Carbon-monoxide utilization rate
SVR	Support vector regression
TT	Top temperature
PI	Permeability index
HL	Heat load
OE	Oxygen enrichment
PCI	Pulverized coal injection
CBV	Cold blast volume
CBP	Cold blast pressure
BP	Blast pressure
PD	Pressure drop
DSB	Descent speed of burden
SC	Silicon content
k-FCV	k-fold cross-validation

element method to analyze the burden falling process. Natsui, Nogami, Ueda, Kano, and Inoue (2011) analyzed the velocities of the burden and gas flow by using the discrete element method and computational fluid dynamics methods.

The model based on the analysis of energy mechanism or numerical simulations has limitations in real ironmaking. Thus, data-driven methods have been used to analyze the BF production process in recent years. For example, Pettersson, Chakraborti, and Saxén (2007) established a feed forward neural network to predict the trends of crucial components in hot metal. Mohanty, Mitra, Saxén, and Chakraborti (2016) employed the k-optimality criterion method to choose the best operating conditions for low costs in a top gas recycling BF. Mitra and Saxén (2014, 2015) designed programs for setting the charging sequence and the chute automatically and achieving the required gas temperature profile. Clugh, Chakraborti, Sindhya, and Jin (2017) used vector-guided evolutionary algorithm to select the effective setting strategy for BF operating parameters. Li, Liu, Jia, and Chen (2015) devised a multi-model control strategy by the k-means and fuzzy support vector machine algorithms to obtain the different burden distribution parameters. Mitra, Saxén, and Chakraborti (2016) summarized the application of evolutionary algorithms in ironmaking.

Most mechanism-based burden distribution models analyze movement, distribution and falling process of the burden. On the other hand, the data-based models demonstrated the feasibility of data-based methods in complex metallurgical processes. With no doubt that those models are helpful for understanding the burden distribution process. But to our knowledge there is no direct relationship analysis between the burden distribution and the energy-consuming index. From the current burden distribution models, it is difficult for BF operators to get the suitable burden distribution parameters for keeping a good state of the BF and improving CMUR.

This paper takes CMUR as an energy-consuming index and presents a decision-making strategy of burden distribution parameters. High CMUR means the reduction of the amount of CO in blast-furnace gas, but suitable adjustment of blast-furnace gas does not cause serious problems for downstream production in an integrated steel plant. That is because blast-furnace gas and high calorific-value coke-oven gas are first mixed and pressurized to ensure that the calorific value and pressure of the mixed gas meet the requirements of a supply of the gas. This guarantees the stable use of the gas in downstream units (Wu, Cao, He, & She, 2009). Thus, this paper aims for a CMUR as high as possible in the decision-making strategy.

The decision-making strategy mainly includes two parts: one is the prediction models that predict the BF state variables based on the burden distribution parameters. The other one uses the predicted states to determine the trend of CMUR's change by a probability-based case-matching model. Based on the trend of CMUR's change, the final decision of burden distribution parameters is obtained. Validation based on the data from an industrial site shows a 70% rate of correctness in the decision-making.

The rest of this paper is organized as follows. Section 2 describes the burden distribution process and its characteristics. The outline of decision-making strategy is introduced in Section 3. Section 4 describes the correlation analysis. Sections 5–7 describe the decision-making strategy in detail. Section 8 gives the verification results based on the actual industrial data. Finally, concluding remarks and future works are summarized in Section 9.

2. Process description and analysis

This section briefly describes the burden distribution process, explains its characteristics, and gives the definition of CMUR.

2.1. Burden distribution process

Burden distribution refers to the process that iron ore and coke are fed into a BF through the charging equipment at the top of a BF. Its main purpose is to control the radial ratio of ore to coke, which is defined as the ratio of radial ore-layer to coke-layer thickness, thereby achieving a suitable distribution of gas flow. A suitable radial ratio of ore to coke guarantees the ore, coke, and the gas flow in full contact and achieves the high CMUR.

The operators adjust the radial ratio of ore to coke by setting the burden distribution parameters that mainly include positions, angles, ore weights, and coke weights. Generally speaking, there are three types of gas flow distribution, i.e., edge-center balance type, edge overdevelopment type, and center overdevelopment type as shown in Fig. 1. The edge-center balance type is what operators expect in the actual production, because when the distribution of gas flow is corresponding to this type, the distribution of burden and gas flow are uniform, which results in low TT, less heat loss and full use of CMUR. When operators replenish lots of coke at the edge of the BF, the distribution of the gas flow becomes the edge overdevelopment type. When operators replenish lots of coke at the center of the BF, the distribution of the gas flow becomes the center overdevelopment type. These two types are not conducive to the improvement of CMUR.

In the actual production, the setting of the burden distribution parameters plays an indispensable role in achieving the maximum utilization rate of CO. Suitable burden distribution parameters determine a suitable distribution of coke, iron ore, and gas flow, eventually a high CMUR is obtained.

2.2. Characteristics of burden distribution process

Many chemical and physical changes occur simultaneously inside the BF. Some variables related to the changes are available, but many of them cannot be detected directly. It is difficult to build a practical mechanism model to accurately describe the effect of burden distribution on the state of the BF. For these reasons, this paper uses the inputs and outputs of the process to build a data-driven model to analyze the effect of the burden distribution on the state of the BF.

The process has the following characteristics, which provide important information for the modeling to be described hereafter.

(1) Accumulativeness and nonlinearity: A BF is a huge metallurgical reactor. The change of the burden distribution in the BF is from the top to bottom, layer by layer. Thus, it is slow and usually takes several hours to reveal the changes in the burden distribution parameters to the state of the BF. This study took 6 h to observe the changes. This timespan is selected based on the actual condition of the BF and operators' experiences, and is also the approximate time period that the burden falls from the top of the furnace to the