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Perception, Decision-making, and Technological Application Research in Blast Furnace Ironmaking Process

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Abstract:

Blast furnace ironmaking a crucial segment within modern steel production, a paradigmatic "black box" model. The optimization of perception and decision-making throughout this process holds paramount significance in enhancing ironmaking efficiency. This research delves into issues such as the incapability of achieving the anticipated fuel ratio in blast furnace ironmaking, the dearth of timely feedback information during the process, and high pollution and energy consumption levels. The research findings imply that by implementing intelligent blast furnace ironmaking, preprocessing blast furnace data, optimizing sinter burden formulation, and leveraging machine learning techniques based on big data to handle the "black box" conundrum, the perception capabilities regarding the blast furnace operating status can be substantially enhanced. Consequently, this leads to optimizing the decision-making procedures, reducing energy consumption, and elevating molten iron quality. Moreover, the intelligent decision-making system grounded in artificial intelligence can effectively mitigate human intervention and augment the overall production stability under complex ironmaking operating conditions. This research proffers novel insights for the intelligent development of the blast furnace ironmaking process and is crucial for propelling the sustainable development of the steel industry.

Keywords: Fuel Ratio Reduction; Intelligent Blast Furnace Ironmaking; Big Data; Deep Learning; Energy Conservation and Emission Reduction.

1. Introduction

Blast furnace ironmaking is one of the core technologies in steel production. It involves the reaction of iron ore and fuels like coke at high temperatures to produce pig iron and exhaust gases. Despite the significant technological advancements in blast furnace ironmaking over the years, several challenges remain unresolved. For instance, in recent times, the global community has imposed increasingly stringent demands on energy consumption and environmental pollution in the steel industry. Against this backdrop, the fuel ratio in traditional blast furnace ironmaking often fails to meet the expected benchmarks, resulting in resource wastage and diminished economic efficiency. Additionally, the feedback information during the ironmaking process is frequently not transmitted on time, and the “black box” phenomenon leads to the uncontrollability of the production process, further intensifying the pressure on environmental protection, energy conservation and emission reduction.

With the rapid development of advanced manufacturing and intelligent technologies, the effective application of novel technological means in the blast furnace ironmaking process to enhance production efficiency, reduce the fuel ratio, and mitigate environmental pollution has become a crucial task within the industry.

In blast furnace ironmaking research, numerous scholars focus on optimizing the fuel ratio. Many studies have indicated that employing high-quality raw materials, fuels, and injection techniques can effectively decrease the fuel ratio and improve ironmaking efficiency [1]. For example, certain research demonstrates that although injection technology can raise the top pressure and theoretically lower the fuel ratio, it encounters issues such as poor pulverized coal quality, coal type fluctuations, and difficulties in parameter adjustment. Researchers have proposed solutions like adopting a reasonable slag-making system to lower the fuel ratio and enhancing screening to reduce the powder entering the furnace [2].

Research based on big data and machine learning is on the rise regarding intelligent blast furnace ironmaking. Current studies reveal that the existence of data silos severely hampers the intelligent transformation of blast furnace production [3]. Owing to the disparity in data acquisition frequencies and dimensions, obstacles to information interconnection occur. In response to this, scholars have put forward solutions such as using the Z-score normalization method to process data and establishing intelligent interconnection platforms to break the information silos and enhance the robustness and real-time performance of models [3, 4].

The environmental pollution issue is also a significant research focus in blast furnace ironmaking. Some researchers have proposed measures such as gas recovery technologies for pressure equalization and discharge, waste gas recovery technologies for pressurized hot blast furnace flues, and the adoption of new cyclone dust collectors to achieve more effective energy conservation and emission reduction goals [5].

This study aims to systematically explore perception, decision-making, and technological application in the blast furnace ironmaking process. Although numerous studies have covered various aspects of blast furnace ironmaking, comprehensive research based on systematic thinking is relatively scarce. This study will fill this void, which will not only enhance the intelligence and efficiency of the ironmaking process but also drive the industry’s transformation towards environmental friendliness. Additionally, this paper will adopt a comprehensive research approach, integrating big data analysis, machine learning, and the latest environmental protection technologies, and propose effective solutions to provide crucial theoretical foundations and practical guidance for achieving the sustainable development of blast furnace ironmaking and help address the global dual challenges of environmental protection and economic efficiency in the steel industry.

2. Intelligent Perception

During the blast furnace ironmaking procedure, raw materials’ varieties and characteristics directly impact the smelting efficiency and product quality. Additionally, air volume, air pressure, and furnace temperature also play crucial roles in influencing the efficiency and product quality of blast furnace ironmaking.

This chapter primarily concerns the applications of Insertion-Type Photoelectric Temperature Sensor, Rail-Type Senso, Starlight Photography High-Temperature Industrial Endoscope, and MIMO-SAR Radar sensors in blast furnace ironmaking.

The insertion-type photoelectric temperature sensor can directly contact or approach high-temperature environments. It accurately measures the furnace interior temperature and promptly detects any abnormal conditions in the hearth. This provides a solid foundation for blast furnace maintenance and inspection. Chengde Steel incorporated the insertion-type photoelectric temperature sensor in its ironmaking blast furnace [6]. Over a 17-month usage period, the sensor remained undamaged, yielding highly satisfactory results.

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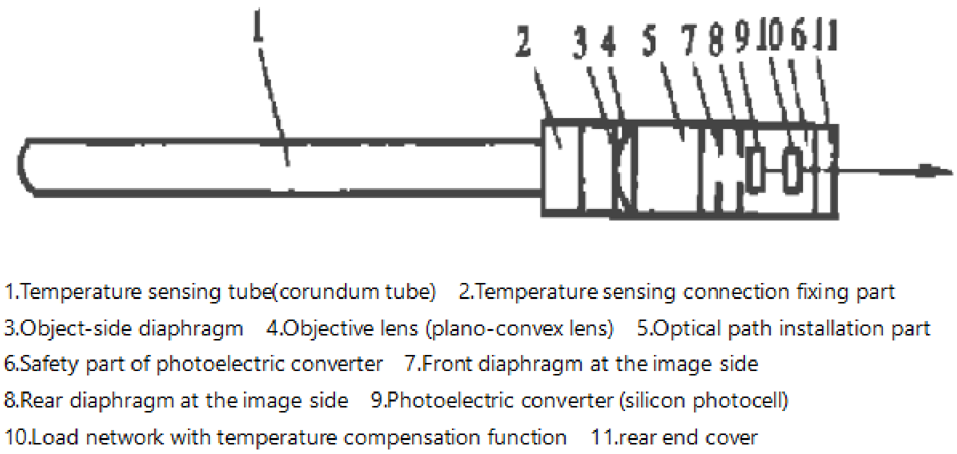

Fig. 1 Schematic diagram of sensor structure and principle [6]

In the ironmaking burden charging system, the dynamic electronic rail weighbridge enhanced with rail-type sensors can resolve the measurement issues related to blast furnace charging [7]. The dynamic electronic rail weighbridge previously utilized consisted of 4 sensors, a steel structure weighbridge frame, and a secondary instrument. The sensors were imported from original columnar sensors from the United States, boasting excellent quality, moisture resistance, stability, and impact resistance.

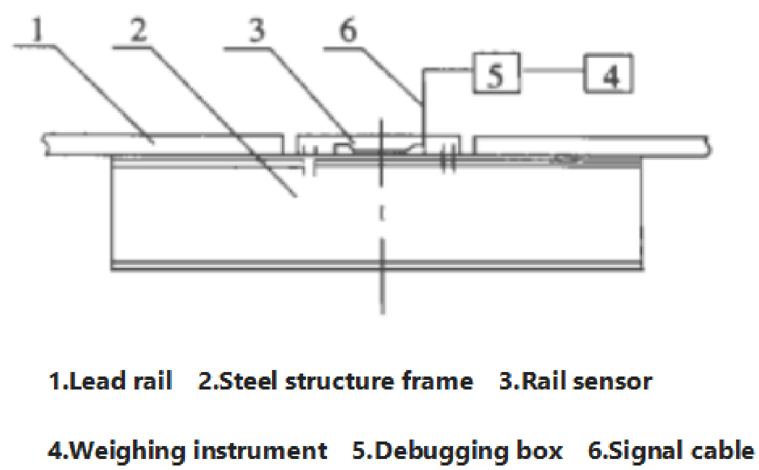

Fig. 2 Fundamentals of rail sensors [7]

Starlight Photography High-Temperature Industrial Endoscope is based on the novel concept of endoscope sensing and detection. It has a starlight imaging system with a large field of view and a large-aperture retrofocus structure. By integrating the water-gas dual-cooling intelligent self-maintenance protection device, the starlight photography high-temperature industrial endoscope was developed. It can steadily acquire clear optical burden surface images in high-temperature, high-dust, and extremely low-light (<0.001 Lux) environments, furnishing crucial data support for blast furnace ironmaking. The optimal installation position and attitude configuration method for the endoscope were proposed through the endoscope imaging area model, the material flow trajectory model, and the gas-dust coupled z-distribution model [8]. This maximizes the effective imaging area and ensures large-area, safe, and stable imaging within a confined space.

A MIMO-SAR imaging system(MIMO-SAR radar) was constructed in a small microwave anechoic chamber by integrating the MIMO array with the SAR imaging system [9]. Near-field MIMO-SAR imaging was conducted on the scaled model of the blast furnace burden surface. The azimuth, elevation, and range errors are all within ±0.011 m, validating that the proposed multi-channel phase center compensation algorithm can effectively correct the phase error when the MIMO-SAR transceiver-separated array utilizes the wavenumber domain imaging algorithm.

In the process of blast furnace ironmaking, diverse sensors exhibit their unique characteristics and application scopes. The insertion-type photoelectric temperature sensor is capable of precisely measuring the internal temperature of the furnace in a high-temperature environment, thus providing a fundamental foundation for blast furnace maintenance and inspection. The rail-type sensor can effectively tackle the measurement issues related to blast furnace charging. Its imported sensor displays excellent quality characteristics and is highly applicable to the burden charging system. The starlight photography high-temperature industrial endoscope can obtain clear images of the burden surface in harsh environments, providing crucial data for blast furnace ironmaking. It is especially suitable for scenarios where the burden surface requires meticulous monitoring. The MIMO-SAR radar conducts high-precision imaging of the blast furnace burden surface and accurately corrects phase errors, offering significant support for the optimization of production parameters.

3. Intelligent Decision-making

The objective of intelligent decision-making in blast furnace ironmaking is to enhance production efficiency, cut costs, improve product quality, extend equipment service life, and strengthen production safety. This entails optimizing burden proportion, stabilizing furnace conditions, conserving energy and reducing consumption, precisely controlling molten iron, predicting equipment malfunctions, and monitoring potential safety hazards. In terms of methodologies, it primarily comprises data analysis and modeling, optimization algorithms, and fault diagnosis and prediction.This chapter presents four blast furnace ironmaking algorithms: the clustering analysis method based on Kohonen self-organizing neural network, the intelligent optimization system for burden structure in sintering-blast furnace ironmaking and its specific methods, the burden structure optimization system based on genetic algorithm, and the regression model based on machine learning for blast furnace area modeling.

A clustering analysis method based on Kohonen self-organizing neural network to optimize the efficiency of blast furnace smelting was introduced in [10]. This method can group the statistical data of blast furnace operation, thereby revealing the relationship between the furnace process's controllable parameters and the economy's key output parameters. The algorithm improves the efficiency and accuracy of data analysis and provides new ideas and methods for the intelligent control of the blast furnace. This system aims to enhance the smelting efficiency and stability of the blast furnace and reduce production costs and energy consumption.

Some researchers used technical means such as linear programming, VB, MATLAB, and artificial neural networks to develop an intelligent optimization system for the burden structure in the whole process of sintering-blast furnace ironmaking [11]. While reducing the sintering cost and the ironmaking production cost optimizes the sinter composition and improves the quality and output of molten iron. Based on the material balance theory, the optimization method of combining MATLAB with linear programming is used to find the optimal sinter burden scheme. The following is the calculation formula for the objective function with the lowest sinter cost.

$$min(\quad Z) \quad = \quad \sum_{i=1}^{n} X_i P_i$$

In the formula: Z represents the lowest cost per ton of iron, in yuan; Xi is the input quantity of the ith raw material, in tons; Pi is the price of the ith input raw material, in yuan/ton; n is the number of raw material types.

Table 1. Calculation results and comparison of cost and main chemical compositions of sinter after optimization [11]

Category	ω(TFe) 1%	ω(CaO) 1%	ω(SiO_2) 1%	ω(MgO) 1%	ω(Al_2O_3) 1%	ω(P) 1%	ω(S) 1%	Basicity	Cost per ton 1 yuan
Before optimization	55.70	10.44	5.36	2.18	2.25	0.08	0.07	1.94	664.81
After optimization	56.05	10.26	5.40	2.14	2.28	0.07	0.06	1.90	661.68

In 2021, an intelligent optimization operating system for burden structure during blast furnace ironmaking was presented [12]. This system is grounded in the blast furnace production of steel companies, applies the principles of blast furnace ironmaking, and utilizes genetic algorithms. With the cost of burden per ton of iron as the objective function, it constructs constraint conditions and penalty functions related to molten iron composition, slag composition, harmful element load, input quantity of raw fuels, and input proportion. It calculates the burden scheme with the lowest cost per ton of iron under corresponding constraint conditions. It aims to reduce the production cost of ironmaking and enhance the quality and output of molten iron.

Subsequently, in 2023, a regression model founded on machine learning was put forward with the aim of realiz-

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ing the automation of ironmaking blast furnaces [13]. This model employs neural networks and tree-boosting models to model several areas of the blast furnace (tuyere, raceway, and shaft) to boost the decision-making efficiency of operators and process engineers. Its objective is to train and test the model based on data generated by CFD simulations through machine learning techniques to rapidly generate data for real-time decision-making. For instance, operation parameters can be adjusted on time according to parameters such as tuyere velocity and raceway flame temperature predicted by the model to ensure the stable operation of the blast furnace.

These intelligent decision-making algorithms offer diverse and highly efficient means for blast furnace ironmaking, enhancing efficiency, stability, and cost-effectiveness. Via precise data analysis, scientific model building, and innovative technology application, they play a crucial role in improving efficiency, optimizing the production process, and enhancing resource utilization.

4. Challenges and Future Outlook

Currently, the intelligent models and perception systems in blast furnace ironmaking are faced with limitations such as data reliance, lack of interpretability, limited adaptability to changes in working conditions, and the impact of environmental factors on the burden surface of the blast furnace. Urgent solutions are needed to address these issues and promote the intelligent development of blast furnace ironmaking.

Intelligent models and perception systems do play certain roles in the process of blast furnace ironmaking. However, numerous limitations still exist. First, in terms of data dependency, the performance of the model is highly dependent on high-quality data. If there are errors, missing values, or outliers in the input data, it will significantly affect the prediction results. Second, there is a shortage of interpretability. Unlike traditional mechanistic models, machine learning models are often black boxes, making it difficult for engineers to understand their decision-making processes. This is unfavorable for evaluating and verifying prediction results as well as diagnosing and analyzing problems. Third, the model has limited adaptability to changes in working conditions. The production conditions of the blast furnace change over time, such as fluctuations in raw material composition, equipment wear, and adjustments to operation parameters. The model needs to adapt quickly to these changes; otherwise, its prediction performance will be affected. Fourth, the burden surface of the blast furnace is influenced by environmental factors such as high temperature and high dust in the furnace, and the image quality is interfered with to a certain extent. Further image processing and optimization algorithms are required to improve accuracy.

In the future, more study related to the algorithm design need to be done. By installing more sensors and monitoring equipment, key parameters such as the temperature, pressure, and gas composition inside the blast furnace can be obtained in real time. Using big data analysis and artificial intelligence algorithms to mine these data deeply can achieve accurate prediction and diagnosis of the furnace condition. For example, developing intelligent burden distribution models and gas flow distribution models can guide the top charging and lower air supply operations, form an appropriate gas flow distribution, improve gas utilization, enhance the permeability of the burden column, and create a long-term, stable, and smooth furnace condition, thereby increasing production efficiency and product quality and reducing energy consumption and cost.

High energy consumption is a major challenge in blast furnace ironmaking. Future efforts will continuously explore methods to improve energy utilization efficiency. On one hand, the hot blast stove technology will be continuously optimized to increase the hot blast temperature, fully utilize the physical heat brought in by the hot blast, promote the combustion of pulverized coal and chemical reactions, and reduce fuel consumption. On the other hand, the waste heat recovery and utilization will be strengthened to recycle the waste heat of high-temperature exhaust gas and slag generated during the blast furnace production process and further improve the comprehensive utilization rate of energy.

5. Conclusions

Currently, the resource utilization efficiency of blast furnace ironmaking needs to be improved, reducing environmental pollution and promoting the transformation and upgrading of the steel industry toward green and intelligent directions. This study focuses on the latest research in the field of blast furnace ironmaking. In terms of intelligent perception, technological innovations in sensors, the development of new endoscopes, and MIMO-SAR can measure the temperature of the burden surface and key parts of the furnace body more clearly. In the aspect of intelligent decision-making, the knowledge base of expert systems is continuously expanded and the reasoning mechanism is optimized. Big data and artificial intelligence algorithms mine patterns to assist in accurate decision-making. Integrating multiple technologies enables the transformation of blast furnace ironmaking from the traditional mode to the intelligent mode, laying a solid foundation for the sustainable development of the steel industry and helping enterprises gain an advantage in the fierce market competition. It plays a crucial role in promoting the optimization and coordinated development of the entire steel industry chain and drives the technological progress of related industries, such as automatic control and data analysis. Future research will focus on further breakthroughs in perception technologies, in-depth optimization of decision-making algorithms, and deep integration of multiple systems to achieve a higher level of intelligence in blast furnace ironmaking and continuously promote the innovation and development of the steel industry.

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