Fuzzy Comprehensive Evaluation Model of Pulverized Coal Digestibility in Blast Furnace Raceway Based on the Fusion of Subjective and Objective Evidence

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In the blast furnace smelting process, the pulverized coal digestibility of the tuyere is an important indicator for studying the combustion status of tuyere. It is the basis for decision making and improvement of pulverized coal injection ratio. A correct and effective assessment is of great significance. In this paper, a fuzzy comprehensive evaluation model based on the fusion of subjective and objective evidence is proposed, which integrates the pulverized coal burnout rate, temperature gradient, combustion zone activity, and uniformity. Pulverized coal burnout rate in the raceway is calculated by the mathematical model. The temperature gradient is obtained by digitizing the tuyere image. The activity and uniformity of the combustion zone are defined by the required temperature for the active state of the blast furnace hearth and average temperature, respectively. Through the expert knowledge and principal component analysis to determine the weights of various indicators, a more accurate and comprehensive model of the pulverized coal digestibility of the raceway in the blast furnace is constructed. The evaluation model is applied to make the application analysis of actual blast furnace off-line data, and the evaluation results are consistent with the actual operation data analysis.

KEY WORDS: blast furnace; pulverized coal; combustion; raceway; radiation image.

1. Introduction

In the ironmaking and steelmaking industry, the energy consumption and pollution emissions of the blast furnace (BF) smelting process account for 60% and 90% of the enterprise’s energy consumption and total emissions, respectively.1,2) After decades of development, the fuel ratio of BF ironmaking is closed to the limit of smelting conditions, so many iron smelting scholars have been devoted to the development of coal instead of coke BF iron smelting technology. Increasing the pulverized coal injection (PCI) ratio can reduce energy consumption and pollution emissions.3,4) According to relevant data, the world’s advanced level of PCI is 180–220 kg/t (the PCI rate is 35%–40%), and the world-class level of PCI is 220–240 kg/t (the PCI rate is 40%–45%) at present, while the average PCI of China’s key iron and steel enterprises in 2010 is 149 kg/t.5) Obviously, China’s BF injection pulverized coal (PC) technology is lower than the world’s advanced level. The difficulty lies in the lack of advanced monitoring methods for the combustion status of the tuyere raceway in the BF.

Although improving the PCI ratio is beneficial to energy conservation and consumption reduction, the sharp increase in PCI ratio will also have adverse effects: (1) A large amount of PC cannot be completely burned in the tuyere raceway (The PC is transported to the tuyere through pneumatic conveying. Due to the high speed of hot air entering, the tuyere raceway zone is formed.), resulting in the accumulation of unburned coal in the furnace, especially in the soft melting zone, which affects the operation of the BF.6) (2) The theoretical combustion temperature drops after BF coal injection.7,8) Most of the PCI into the BF is burned out in the raceway, the higher combustion rate of PC is the necessary condition for improving the operation ratio of PCI. Therefore, the real-time monitoring of the raceway can feedback the PC digestion to the BF operators in time, which is conducive to the operator’s grasp of the coal injection system and time, and solve the problem of large inertia and large time lag of the BF. It is crucial for the development of replacing coke with coal.

At present, the evaluation of the PC combustion status in the BF tuyere raceway is mainly divided into: 1) Experienced, semi-empirical and numerical methods are used to calculate the burnout rate of PC. When Yang Tianjun et al.9) Cen Kefa et al.10) Shen et al.11,12) Guo et al.13) calculated the burnout rate of PC; they assumed that the kinetic parameters of PC are constant or only a function of temperature, without considering the influence of PC composition on the kinetic parameters. Fu Weibiao14) found a general rule of PC combustion by analyzing a large amount of experimental data. Only by knowing the industrial analysis value of PC,
it is possible to uniformly calculate the kinetic parameters of PC combustion reaction, thus solving the irregularity that has puzzled people for a long time in studying the kinetic parameters of coal char combustion. On this basis, Chen et al.\(^1\) established the general model of PC combustion rate of BF combined with the PCI process of the BF. 2) Monitoring flame combustion status by electronically coupled device (CCD). The tuyere is the only peephole that can observe the state of a closed BF in real time. The radiation image of tuyere collected by CCD is an intuitive and effective evidence for evaluating the combustion status of PC. Wen et al.\(^2\) N. Kurihara et al.\(^3\) R. Zhang et al.\(^4\) reconstructed the temperature distribution of the raceway zone by image processing technology, and analyzed the PC combustion. Zhou et al.\(^5\) firstly proposed the definition of uniformity and activity of each region and circumferential direction of BF tuyere combustion zone, and combined with the temperature distribution, studied the working state of tuyere combustion zone.

The above literatures only study the combustion status of PC in the raceway from a single index such as PC burnout rate or tuyere radiation image. There is no systematic and comprehensive evaluation model to evaluate the PC digestibility of the BF. Based on the previous studies, this paper constructs an evaluation index system including the PC burnout rate, temperature gradient, and the activity and the uniformity of the combustion zone in the raceway. It combines the advantages of the theoretical model of PC combustion with collection of radiant images of raceway zone. Then, using the expert experience and principal component analysis to weight the evaluation index, the final evaluation model is obtained. This evaluation model provides a more reliable basis for the decision-making of replacing coke with coal and reducing energy consumption in the BF.

2. Theory

2.1. Pulverized Coal Combustion Model

The basic assumptions for the mathematical model of PC combustion in the raceway are: (1) The temperature and pressure of the gas in the raceway remain stable; (2) Pulverized coal is preferentially burned than coke; (3) The combustion of high temperature PC is mainly based on \(2C + O_2 = 2CO\) reaction; (4) The internal temperature of the PC particles is uniform; (5) Does not consider the effect of volatilization on the particle size of PC.

2.1.1. Particle Size Equation

Assuming that the PC burning rate is \(G_c\), the PC mass equation is expressed as

\[
\frac{dm}{dt} = G_c \quad \text{.......................... (1)}
\]

2.1.2. PC Combustion Rate

The factors affecting PC combustion state include PC particle size, temperature, ambient oxygen gas integral number, oxygen diffusion coefficient, etc. Chen et al. according to the general law of coal combustion proposed by Fu Weibiao, has presented the general expression of kinetic parameters of PC combustion.

\[
\begin{align*}
    k_{0,ch} &= 4.109 \left( F_z + 27 \right)^{18.98} \times 10^{-22} \\
    &\times \left[ 1 - \left( 0.8363 + 0.7082Fb + 0.2150Fb^2 \right) \\
    &+ 0.0267Fb^3 + 0.00107Fb^4 \exp \left( -Fb \right) \right], \quad Fb \geq -2; \\
    k_{0,cb} &= 4.109 \left( F_z + 27 \right)^{18.98} \times 10^{-22} \\
    &\times \left[ 0.1637 + 0.868 \exp \left( \frac{0.51}{Fb + 1.59} \right) \right], \quad Fb \leq -2.
\end{align*}
\]

where, \(k_{0,cb}\) is the reaction frequency factor, \(m\cdot s^{-1}\); \(Fz\) is the coal quality index, and given by \(Fz=\left(V_{ad}+M_{ad}\right)^2\times C_{ad} \times 100\); \(Fb\) is the burnout state parameter, the expression equation is as follows

\[\begin{align*}
    Fb &= \ln \left[ \frac{k_{0,cb}D}{D_Nu} \right] \\
    &\times Y_{0,cb} \exp \left( - \frac{E}{RT} \right) \quad \text{.......................... (3)}
\end{align*}\]

where, \(Y_{0,cb}\) is the mass fraction, \(Y_{0,cb} = 2.75Y_{0,c}\); \(D_{h}\) is the gas diffusion coefficient on the particle surface, \(m^2\cdot s^{-1}\). \(E\) is activation energy which is set to 180 kJ\cdot mol\(^{-1}\). \(Nu\) is the diffusional criterion of Nusselt. \(R\) is the gas constant. \(k_{0,cb}\) and \(Fb\) are calculated by an iterative method until \(\left(k_{0,cb}\right)_{\text{new}} - \left(k_{0,cb}\right)_{\text{old}}\) is within the allowable error area. The initial value is set as \(k_{0,cb}=4.109 \times (F_z + 27)^{18.98} \times 10^{-22}\).

Because the combustion rate is related to \(Fb\) and \(k_{0,cb}\), a unified general combustion rate \(G_c\) is obtained by fitting the experimental data. Particle burning rate is given by \(G_c = 2\pi d_c \rho D_c G_{c,cb} \cdot \text{kg} \cdot \text{s}^{-1}\).

2.1.3. Calculation of Burnout Rate

The burnout rate of PC can be calculated by:

\[G = \left( V_{ad} + w_c \right) / \left( 1 - A_{ad} \right) \quad \text{.......................... (4)}\]

where, \(V_{ad}\) is the mass fraction of released volatiles, and \(w_c\) is burned carbon mass fraction, and \(A_{ad}\) is PC ash mass fraction.

2.2. Temperature Distribution Calculation According to Bicolor Method

According to Planck’s theorem and Wien approximation formula, when the radiator temperature is lower than 3 000 and the wavelength \(\lambda < 1\), the monochromatic radiance of the radiator is expressed as:

\[L(\lambda,T) = e(\lambda,T) C_1 \lambda^{-\frac{5}{2}} e^{\frac{C_1}{\lambda T}} \quad \text{.......................... (5)}\]

where, \(C_1, C_2\) are the first and second radiation constants.
respectively. \( C_1 = 3.7418 \times 10^{-16} \text{ W·m}^2; \) \( C_2 = 1.4338 \times 10^{-2} \text{ m·K} \); \( T \) is the radiator temperature, \( K; \) \( \varepsilon(\lambda, T) \) is the spectral emissivity of the radiator, dimensionless.\(^{20}\)

\[
R = H \cdot K_r \varepsilon(\lambda_r, T) \frac{C_1}{\pi} \lambda_r^{-5} \exp \left( \frac{C_2}{\lambda_r T} \right)
\]

\[
G = H \cdot K_g \varepsilon(\lambda_g, T) \frac{C_1}{\pi} \lambda_g^{-5} \exp \left( \frac{C_2}{\lambda_g T} \right)
\]

\[
B = H \cdot K_b \varepsilon(\lambda_b, T) \frac{C_1}{\pi} \lambda_b^{-5} \exp \left( \frac{C_2}{\lambda_b T} \right)
\]

where \( K_r, K_g, K_b \) are defined as the spectral response coefficients of the \( R, G, \) and \( B \) color channels of the CCD, respectively, which can be used to characterize the color value of CCD output and the photoelectric conversion efficiency of monochromatic radiance at the corresponding base color wavelength.

\( \lambda_r = 700.0 \text{ nm}, \lambda_g = 546.1 \text{ nm}, \) and \( \lambda_b = 435.8 \text{ nm} \) are the color wavelengths of \( R, G, \) and \( B \) respectively. Any two colors of the formula (3) can be used to obtain the bicolor temperature measurement formula (take \( R, G \) for example).

\[
T = \frac{C_2 \left( \frac{1}{\lambda_r} - \frac{1}{\lambda_g} \right)}{\ln \left( \frac{L(\lambda_r, T)}{L(\lambda_g, T)} \right) + 5 \ln \frac{\lambda_r}{\lambda_g} - \ln \left( \frac{\varepsilon(\lambda_r, T)}{\varepsilon(\lambda_g, T)} \right)}
\]

2.3. Definition of Activity and Uniformity of Combustion Zone

The evaluation of the uniformity and the activity of combustion zone of BF tuyere are very important for BF smelting.\(^{21,22}\) They are important factors affecting the initial distribution of gas flow and the quality of molten iron. They are also of great significance to the longevity, high efficiency and stable running of BF.\(^{23}\) For a long time, the uniformity and the activity evaluation system of BF combustion zone have not been effectively established. Zhou et al. firstly proposed the combustion zone uniformity and activity evaluation system. The evaluation system can provide real-time judgment of the working status of the BF tuyere combustion zone. The uniformity of the tuyere combustion zone is proposed to evaluate the uniformity of each region in the hearth, and is useful for judging the temperature distribution in the hearth and the distribution of PC in various regions of the hearth. The activity is proposed to evaluate the activity of the hearth, and the activity of the hearth will directly affect the quality of the molten iron and the life of the BF. In addition, the activity evaluation is helpful to judge the degree of digestion of PC. In this paper, in order to improve the accuracy and rationality of the model, uniformity, and activity of the tuyere combustion zone are included in the evaluation index system of the PC digestibility evaluation model. Baotou Steel blast furnace has 30 tuyere at equal distances in the circumferential direction, and the two adjacent tuyere are assumed as one region, which is shown in Fig. 1.

2.3.1. Uniformity Index

By measuring the temperature of the tuyere images collected by CCD, the average temperature of the tuyere combustion zone and the temperature of each region are obtained. The local area uniformity index of the tuyere combustion zone is represented by \( U \):

\[
U = \frac{100}{\sqrt{\frac{1}{n} \sum_{i=1}^{n} (\bar{T} - T_i)^2}}
\]

where, \( \bar{T} \) represents the average temperature of the combustion zone, and \( T_i \) represents the temperature of each region, and \( n \) is the number of regions.

2.3.2. Activity Index

The activity of the BF tuyere combustion zone is of great significance for improving the quality of molten iron and maintaining the stability of the BF. The activity index of the tuyere combustion zone is given by:

\[
A = \frac{1}{n} \sum_{i=1}^{n} \frac{T_i}{\bar{T}_A}
\]

where, \( \bar{T}_A \) represents the temperature required for the tuyere to be active.

3. Experiment and Results

3.1. Tuyere Raceway PC Burnout Rate Calculation

In the process of calculation, the particle size distribution of PC is assumed to be uniform, and the influence of the particle size of PC on the residence time is not considered. The residence time of PC in the gyration zone is 25 ms. The analysis value of PC and furnace dust industry is shown in Table 1.

![Fig. 1. Distribution diagram of blast furnace ironmaking process and tuyere combustion zone. (Online version in color.)](image)

Unburned PC will be discharged with the furnace dust and slag in the BF. According to the Baoshan steel research, the ratio of unburned PC in the slag and furnace ash is 1:9. The PC burnout rate is calculated by the formula (4), where the burned carbon mass fraction \( w_c \) is obtained by analysis of unburned PC. In order to solve the multi-scale problem of different parameters of the BF, ten sampling periods are
selected, so that the evaluation indexes are integrated. PC burnout rate is shown in Fig. 2.

Comparison with literature [22] data, the calculated PC combustion rate is basically between 70% and 80%. It shows that the BF smelting is basically in a long-term stable state, and occasional fluctuations are in line with actual production work.

3.2. Tuyere Raceway Temperature Calculation

Due to the complex production environment of the BF, there is a large amount of noise interference in the image of the tuyere, and there are halo, spot and PC occlusion. In order to improve the accuracy of temperature distribution detection, the image is denoised and segmented by digital processing technology. Then, the image is grayscale, and the gray value of each pixel is used to represent the radiation brightness of the monomer. The temperature of each pixel is calculated by the formula (7), and then, the temperature distribution and the average temperature of each region can be obtained. Figures 3(a) and 3(b) are the radiation image and temperature distributions of 15 regions of Baotou Steel BF at the same time, respectively.

3.2.1. Temperature in Each Region

The average of the temperature distributions of each region characterizes the temperature of the region, and the temperature of each region in the first sampling period is shown in Fig. 4.

3.2.2. Temperature Deviation and Temperature Gradient

We calculate the average temperature of each region in the same sampling period and use it to represent the average temperature of the tuyere combustion zone during the sampling period. The formula is as follows:

$$\bar{T}_c(k) = \frac{1}{n} \sum_{i=1}^{n} T_i(k)$$

where: $\bar{T}_c(k)$ is the average temperature of the tuyere combustion zone for the $k$ sampling period, and $n$ is the number of regions, and $T_i(k)$ is the average temperature of the $i$th region. The temperature gradient of each sampling period is obtained by backward difference, which is expressed as follows:

$$\Delta T(k) = |\Delta T_c(k) - |\Delta T_c(k-1)|, k = 2,3,\ldots, 11 \ldots (11)$$

where, $\Delta T_c(k) = \bar{T}_c(k) - \bar{T}_c(k-1), k = 2,3,\ldots, 11$, which
represents the temperature deviation of the combustion zone at the kth sampling time. Then the combustion zone temperature deviation and temperature gradient are shown in Fig. 5.

3.3. Tuyere Raceway Uniformity Index and Activity Index

3.3.1. Uniformity and Activity in Different Regions

The calculation of the uniformity of each region is expressed by the deviation between the average temperature of each tuyere and the average temperature of the combustion zone. For the unified evaluation index type, the deviation which is smaller and better index will be changed to the bigger and better index.

\[ U_i = \frac{100}{(\bar{T}_c - T_i)^2} \] .......................... (12)

where \( T_i \) is the uniformity of the combustion zone and \( T_i \) is the average temperature of the ith region.

The activity of each region is the ratio of the average temperature of each tuyere to the temperature required for the active combustion. If the ratio is greater than 1, the tuyere is considered to be active. If the ratio is less than 1, the activity is less active.

\[ A_i = \frac{T_i}{\bar{T}_A} \] .......................... (13)

In the formula, \( \bar{T}_A \) is the temperature required for the combustion zone to be active. Comprehensively investigate the temperature distribution of the BF tuyere and the operating parameters of the BF, we set \( \bar{T}_A \) to 2053°C. The activity and uniformity of each region of the combustion zone in the first sampling period are shown in Fig. 6. From Fig. 6, it can be seen that the uniformity and activity of different regions are different. This is due to the influence of the burning rate of PC. From Fig. 3(a), it can be seen that there is a large amount of PC in the ninth tuyere, which proves that the burning rate of PC in this region is low at this time, and affects the uniformity index of this region. The activity can be judged by the brightness in the radiation image. The sixth, eleventh and fifteenth tuyere in Fig. 3(a) have higher brightness, which proves that the region is more active. The result is consistent with Fig. 6.

3.3.2. Combustion Zone Uniformity and Activity

The uniformity and activity of the combustion zone during the sampling period are obtained by averaging the uniformity and activity of each region, the formulas are (8) and (9), which are shown in Fig. 7. It can be seen from Fig. 3 that the PC has a lower burnout rate in the first and sixth sampling periods, which also affects the uniformity of the combustion zone at the sampling time.

3.4. Principal Component Analysis and Expert Experience Weighting

The above four indicators are used to comprehensively judge the pulverized coal digestibility of the tuyere pipeline, and the index system for evaluating the digestibility of the pulverized coal pulverized coal is established, as shown in Fig. 8.

Through the empowerment of four evaluation indicators, the influence of four indicators on the pulverized coal digestibility of the raceway is integrated, and the fuzzy comprehensive evaluation of multi-angle and multi-faceted information fusion is realized. The weight of the evaluation index reflects the importance of each indicator to the evaluation target, and the corresponding weights need to be allocated reasonably for each indicator. The methods for determining weights can be divided into two categories: subjective weighting and objective weighting. The subjective weighting method relies mainly on expert experience to determine the weight. Although it is easy to implement, it is subjective. The objective weighting method is based
on the process parameters in the actual operation of the BF, and obtains the weight of the index through mathematical operations. The determined weight is more objective. In the process of transforming the original variable into the main component, the principal component analysis method simultaneously forms the weight of the reaction evaluation index and the evaluation object to calculate the comprehensive evaluation value. Such evaluation weight selection overcomes the influence of subjective factors and helps ensure objective response to the actual relationship between the samples. In view of the rich operational experience of the BF ironmaking industry and the large amount of operational data, this paper combines the principal component empowerment with expert experience. Through the statistical analysis of the BF operation data, the principal component analysis method and expert experience are used to determine the weight between each factor, so that the weight assignment is more accurate.

Table 2 shows the expert experience weighting value and principal component analysis weighting value, which are denoted as $U_E$ and $U_p$ respectively. Finally, $A=0.4U_E+0.6U_p$ is used to empower each evaluation indicator.

### 3.5. Fuzzy Comprehensive Evaluation Results

According to the actual operation and management requirements of the blast furnace, the pulverized coal digestibility evaluation set $L$ of the raceway contains four evaluation grades: “excellent”, “good”, “general” and “warning”, which are denoted as $l_1$, $l_2$, $l_3$, $l_4$, respectively. That is $L = \{l_1, l_2, l_3, l_4\}$. The weights of each evaluation index are obtained through the authoritative fusion expert experience and principal component analysis. The weights of each evaluation index are obtained by integrating authoritative expert experience and principal component analysis, which is expressed as $R_i(i=1, 2, 3, 4)$. The final evaluation vector is $B=AR=[b_1, b_2, b_3, b_4]$. Finally, the fuzzy evaluation results of ten sampling periods are shown in Fig. 9.

It can be seen from Fig. 8 that the fuzzy evaluation results combine the influencing factors of the PC digestibility in the raceway. The evaluation results of the eighth sampling period are the best, and the optimal values of the PC burnout rate, the raceway temperature gradient, the combustion zone uniformity and the activity are the tenth, second, second and ninth sampling periods, respectively. During the above sampling period, the combustion zone of the second and tenth sampling periods is less active, resulting in an evaluation result lower than the eighth sampling period. The pulverized coal combustion rate, the uniformity of the combustion zone and the temperature value of the raceway in the ninth sampling period are low, resulting in the evaluation results being in ‘ordinary’. The eighth sampling period with the best evaluation results has better values in each evaluation index. On the contrary, the first sampling period is not...
prominent in each evaluation index, resulting in a ‘bad’
evaluation result. In the evaluation results, the early warning
area represents poor PC digestibility and the BF operating
parameters need to be adjusted. The multi-information fuzzy
comprehensive evaluation can eliminate the one-sidedness
of the single evaluation index, and can combine the infor-
mation of multiple levels and different fields to improve the
reliability of the evaluation results.

4. Conclusion

Aiming at the need of monitoring the digestibility of PC
in the combustion zone, this paper analyzes the influencing
factors of PC digestibility evaluation, and constructs an
evaluation index system and fuzzy comprehensive evalu-
ation model for PC digestibility of BF tuyere combustion
zone, which avoids the phenomenon that a single evaluation
index covering the actual situation. Through the analysis
of the actual online detection information, the evaluation
results of the model are close to the actual operating condi-
tions, and have strong maneuverability, which is beneficial
to the BF operators to adopt appropriate air supply system,
thermal system, and coal injection system. It is helpful for
discovering the hidden dangers of hearth heating or cooling
in time. The research results can provide decision-making
assistance for the optimization operation of the new tech-
nology of replacing coke with coal in the BF ironmaking
industry,25,26) and improve the efficiency of replacing coke
with coal operation.

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