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REAL-TIME ESTIMATE OF BLAST FURNACE THEORETICAL COMBUSTION TEMPERATURE BASED ON THE VARIATION OF GAS UTILIZATION RATE AND COKE RATIO[1]

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Abstract

The thermal state is an important index to evaluate the blast furnace (BF) operation. Method of rapid and accurate real-time estimation of the thermal state has always been one of hot research topics. Although the measurements of hot metal temperature, silicon content and other indicators are used to judge the thermal state inside BF, it is difficult to be applied in practical production as a result of hard real-time detection. A method of forecasting the trend of theoretical combustion temperature (TCT) by using real-time detected gas utilization rate and coke ratio is developed in present work. Firstly the relationship between gas utilization rate and direct reduction rate is established based on the A.H.Pamm joint calculation method. Then the effect of gas utilization rate on coke ratio is calculated based on the relationship between direct reduction rate and coke ratio. Finally, according to the different value between the variation value of coke ratio which caused by gas utilization rate and the practical coke ratio, an new index which associates with gas utilization rate and coke ratio is proposed to predict the trend of TCT. It can be concluded that, as for a 4,747 m^3 large-scale BF, the coke ratio decreases by 4.5 $kg\cdot(tHM)^{-1}$ while the gas utilization rate increases by 1%. The real-time estimating results of TCT are in good agreement with theoretical results, which indicates that the proposed method to forecast TCT in present work is applicable to be used in practical production.

Key words: Blast furnace; Gas utilization rate; Theoretical combustion temperature; Real-time estimate.

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1 INTRODUCTION

The thermal state of blast furnace (BF) is very important, especially in hearth. It is a key point of deciding the requirement of heat for BF and the consumption of fuel.[1] The theoretical combustion temperature (TCT) of the tuyere is one of the most important parameters to evaluate and measure the thermal state of hearth. It demonstrates by theoretical research and practical production that maintaining a certain value of TCT is very significant for heat exchange between gas and burden, especially for the temperature of hot metal.[2,3] In theoretical research, TCT can be used to evaluate the thermal state of BF accurately. In practical production, the control of the TCT can stabilize the thermal state of BF.
TCT is the highest temperature of BF gas produced by fuel combustion in hearth. During the process of combustion, the fuel obtain all chemical heat produced by combustion reaction and physical heat which is brought in by blasted hot air and raw materials.[4] At present, there are many methods can be used to calculate the TCT, such as calculation on BF TCT based on burning 1 kg·$(tHM)^{-1}$ carbon and blasting 1 m^3·$(tHM)^{-1}$ hot air in tuyere area[5] and calculation on TCT based on empirical equation.[6] These methods all can be used to calculate the TCT accurately, but the calculation process is too complex and cost much time. So these calculation methods are widely used in theoretical research but not in practical production. In practice, a simple and timely way to judge the variation trend of TCT is more practical and useful. In this paper, a flexible and real-time calculation method of forecasting the trend of TCT is established. The method can forcast the change tendency of TCT rapidly and timely. It is simple and timesaving. The forecast results are in good agreement with theoretical results by using practical data of a iron and steel company.

2 MATERIALS AND METHODS

At present, there is no method which directly solve the effect of gas utilization rate on coke ratio. However, the effect of direct reduction rate on coke ratio can be calculated through A.H.Pamm joint calculation method[7]. So in this paper, a relational expression between gas utilization rate and direct reduction rate is researched at first. Then based on these relations, the relationship between gas utilization rate and coke ratio is established.

2.1 Establishment of the Relationship Between Gas Utilization Rate and Coke Ratio

In BF, gas utilization rate is a ratio between carbon dioxide produced by carbon monoxide indirect reduction and the total carbon monoxide of BF (Equation 1).

$$\eta_{CO} == \frac{I_2 + I_3}{I_1 \times \frac{22.4}{12}} \times 100\% \quad (1)$$

Where I_1 means the total mass of pneumatolytic carbon in BF, kg·$(tHM)^{-1}$; I_2 means the volume of carbon dioxide produced by reduction of high valent oxide in BF, m^3 $(tHM)^{-1}$; I_3 means the volume of carbon dioxide produced by carbon monoxide indirect reduction of FeO in BF, m^3·$(tHM)^{-1}$. And I_1 can be calculated by Equation 2.

$$I_1 = w(C_{coke}) + w(C_{coal}) - w(C_{dust}) - 10[C] \quad (2)$$

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Where $w(C_{coke})$ is the mass of carbon of coke, kg·(tHM)$^{-1}$; $w(C_{coal})$ is the mass of carbon of coal, kg·(tHM)$^{-1}$; $w(C_{dust})$ is the mass of dust, kg·(tHM)$^{-1}$; [C] is the percentage of carbon of hot metal, %.

$$w(C_{coke}) = CR \times (C)_{coke,\%} \tag{3}$$

$$w(C_{coal}) = PCR \times (C)_{coal,\%} \tag{4}$$

$$w(C_{dust}) = U_{dust} \times (C)_{dust,\%} \tag{5}$$

Where CR is the coke ratio, kg·(tHM)$^{-1}$; PCR is the coal ratio, kg·(tHM)$^{-1}$; U_{dust} is the mass of dust, kg·(tHM)$^{-1}$; $(C)_{coke,\%}$ is the percentage of total carbon in coke, %; $(C)_{coal,\%}$ is the percentage of total carbon in coal, %; $(C)_{dust,\%}$ is the percentage of total carbon in dust, %. And I_2 can be calculated by Equation 6.

$$I_2 = \frac{22.4}{160} \times w(Fe_2O_3) + \frac{22.4}{87} \times w(MnO_2) \tag{6}$$

Where $w(Fe_2O_3)$ is the total mass of Fe_2O_3 in BF, kg·(tHM)$^{-1}$; $w(MnO_2)$ is the total mass of MnO_2, kg·(tHM)$^{-1}$.

$$w(Fe_2O_3) = [A \times (Fe_2O_3)_{A,\%} + \Phi \times (Fe_2O_3)_{\Phi,\%} - U_{dust} \times (Fe_2O_3)_{dust,\%}] \tag{7}$$

$$w(MnO_2) = A \times (MnO_2)_{A,\%} \tag{8}$$

Where A is the mass of ore, kg·(tHM)$^{-1}$; Φ is the mass of flux, kg·(tHM)$^{-1}$; $(Fe_2O_3)_{A,\%}$ is the percentage of Fe_2O_3 in ore, %; $(Fe_2O_3)_{\Phi,\%}$ is the percentage of Fe_2O_3 in flux, %; $(Fe_2O_3)_{dust,\%}$ is the percentage of Fe_2O_3 in dust, %; $(MnO_2)_{A,\%}$ is the percentage of MnO_2 in ore, %. And I_3 can be calculated by Equation 9.

$$I_3 = 10[Fe] \times \left(1 - r_d - r_{H_2}\right) \times \frac{22.4}{56} \tag{9}$$

Where [Fe] is the percentage of ferrum in hot metal, %; r_d is the direct reduction rate, -; r_{H2} is the reduction rate that reducted by hydrogen, -.

$$r_{H_2} = \frac{56V_{H_2} \times \eta_{H_2}}{22.4 \times 10[Fe]} \tag{10}$$

Where V_{H2} is the total volume of hydrogen in BF, m^3·(tHM)$^{-1}$; η_{H2} is the utilization rate of hydrogen, %.

$$\eta_{H_2} = \left(0.88\eta_{CO} + 0.1\right)\text{[1]} \tag{11}$$

Where η_{CO} is the gas utilization rate, %. Based on all the equations above, the relationship between gas utilization rate and direct reduction rate is obtained.

The change of direct reduction rate will lead to the heat change of direct reduction and indirect reduction. According to the A.H.Pamm joint calculation method,[7] as the consumption of carbon through direct reduction increases by 1 kg·(tHM)$^{-1}$, the change of coke ratio can be calculated. While the carbon through direct reduction increases 1 kg·(tHM)$^{-1}$, the direct reduction rate increases 0.005 equivalently[7]. That is mean that the effect of direct reduction rate on coke ratio can be calculated. Then, combining the relationship between gas utilization rate and direct reduction rate which are calculated above, the effect of gas utilization rate on coke ratio can be calculated.

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2.2 Results of Gas Utilization Rate on Coke Ratio

Through the relationship between gas utilization rate and direct reduction rate and the relationship between direct reduction rate and coke ratio, the effect of gas utilization rate on coke ratio is calculated. Taking a 4,747 m³ large-scale BF of a steel works as an example, one month production data are applied and the decreased value of the coke ratio as gas utilization rate increases by 1% is calculated. The results are shown in Figure 1.
About the BF, some raw material data and operating parameters are shown from Table1 to Table 5:

Table 1. Chemical composition of fuel in BF (weight %)

Fuel	Fixed carbon	Ash	Volatile	Moisture
Coke	86.63	12.31	1.06	0.00
Coal	73.24	9.64	16.12	1.00

Table 2. Chemical composition of fuel ash in BF (weight %)

Fuel	SiO_2	Al_2O_3	CaO	MgO	FeO	Else
Coke	47.99	38.15	1.71	0.20	6.29	5.66
Coal	51.93	32.46	7.14	1.35	4.91	2.21

Table 3. Chemical composition of coke volatile in BF (weight %)

Fuel	CO	CO_2	H_2	N_2	S
Coke	35	36.5	10	18	0.5

Table 4. Chemical composition of coal volatile in BF (weight %)

Fuel	C	H	O	N	S
Coal	43	24	27	5.5	0.5

Table 5. Operating parameters of the BF

Item	Blast flow rate (m^3•min^{-1})	Blast humidity (g•m^{-3})	Blast temperature K
Data	6716	12.68	1521
Item	Air temperature K	Ore consumption kg•$(tHM)^{-1}$	Oxygen flow rate (m^3•min^{-1})
Data	295	1571	280
Item	Oxygen enrichment rate %	Carrier gas temperature K	Carrier gas flow (m^3•h^{-1})
Data	3.18	348	57
Item	Coke rate kg•$(tHM)^{-1}$	Coal rate kg•$(tHM)^{-1}$	Gas utilization rate %
Data	291	196	52

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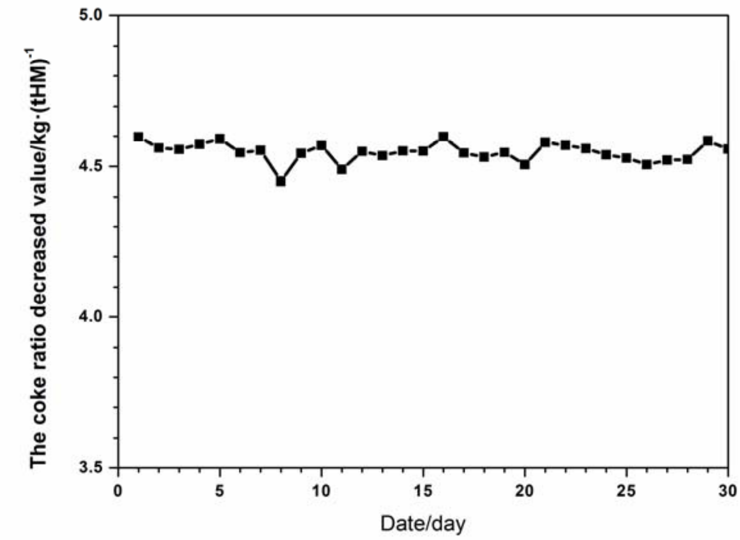

Figure 1. The coke ratio decreased value as the gas utilization rate increases by 1%.

From Figure 1, it shows that the results of the coke ratio decreased value during a month is stable and the average value is 4.5 kg·(tHM)$^{-1}$. That is mean that the coke ratio decreases about 4.5 kg·(tHM)$^{-1}$ as the gas utilization rate increases by 1%.

2.3 Establishment of the Relationship Between Coke Ratio and TCT

Based on the mass balance and heat balance of tuyere area and direct reduction area, a TCT calculation model is established. The flow chart of TCT calculation model is shown in Figure 2. In this model, the chemical reaction of tuyere area and direct reduction area are shown in Table 6. The TCT and the effect of coke ratio on TCT can be calculated by the model. Similarly, the same BF is taken for an example, the same month production data are applied, and the results of TCT are also calculated.

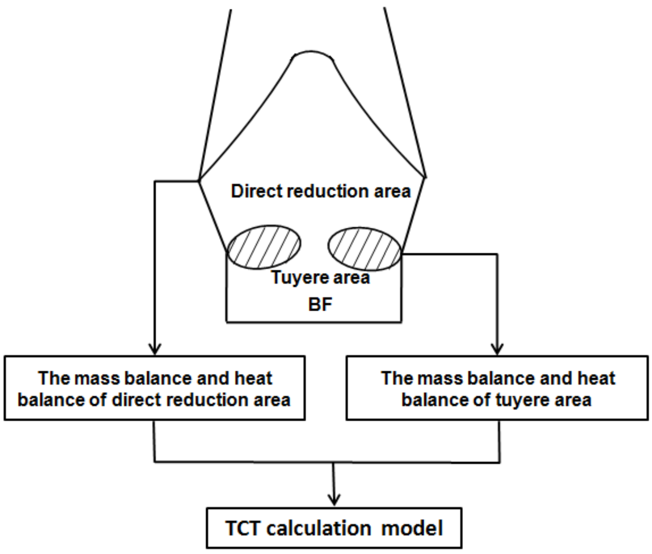

Figure 2. The flow chart of TCT calculation model

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Table 6. The chemical reactions of tuyere area and direct reduction area

Tuyere area	Direct reduction area
$2C+O_2=2CO$	$FeO+C=Fe+CO$
$2H_2+O_2=2H_2O$	$SiO_2+2C=Si=2CO$
$H_2O+C=H_2+CO$	$MnO+C=Mn+CO$
$Coal \rightarrow C+H_2O+H_2+N_2+O_2+Ash$	$P_2O_5+5C=2P+5CO$
	$TiO_2+2C=Ti+2CO$
	$FeS+CaO+C=CaS+CO+Fe$
	$H_2O+C=H_2+CO$
	$CaCO_3+C=CaO+2CO$

In this paper, the calculated TCT is called theoretical results in order to distinguish the forecast results below. It can obtain the decreased value of TCT as the coke ratio decreases 1 kg·(tHM)$^{-1}$. With the same data of the BF above, the average value is about 1.94 K.

3 RESULTS AND DISCUSSION

Based on the effect of gas utilization rate on coke ratio and the relationship between coke ratio and TCT, a real-time estimating equation that predict the trend of TCT is formed.

$$TCT_1 = [(\eta_{CO1} - \eta_{CO0}) \times (-4.5) - (CR_1 - CR_0)] \times 1.94 + TCT_0 \tag{12}$$

Where TCT_1 is TCT at current moment, K; TCT_0 is TCT at previous moment, K; η_{CO1} is gas utilization rate at current moment, %; η_{CO0} is gas utilization rate at previous moment, %; CR_1 is coke ratio at current moment, kg·(tHM)$^{-1}$; CR_0 is coke ratio at previous moment, kg·(tHM)$^{-1}$.

As we know, the gas utilization rate and the coke ratio are instantaneous values in steel works. The previous moment TCT can be calculated by model established above. If the gas utilization rate, the coke ratio and the TCT of previous moment are known, the TCT of current moment can be calculated according to the Equation 12,.

In order to forecast the TCT more convenience for practical workers, an index λ is defined.

$$\lambda = (\eta_{CO1} - \eta_{CO0}) \times (-4.5) - (CR_1 - CR_0) \tag{13}$$

According to the Equation 13, it obvious shows that as λ increases, the TCT increases, and λ decreases, the TCT decreases. They have the same change tendency. Similarly, the data of the same BF are used to testify the forecast equation. These data are instantaneous value. There is ten minutes interval between every two adjacent data.

The results of λ and theoretical TCT which calculated by model established above are shown in Figure 3

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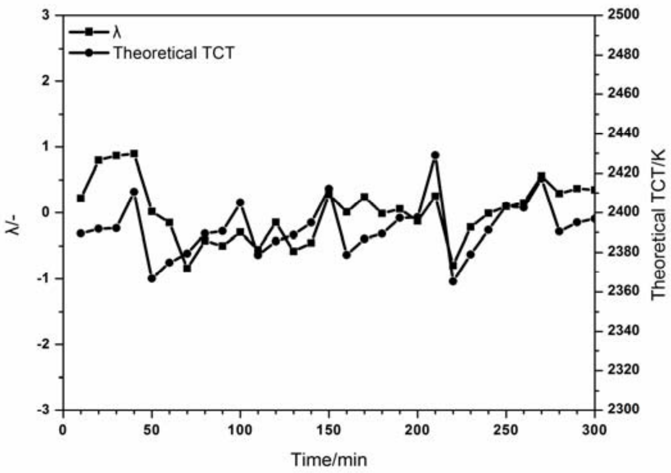

Figure 3. The change tendency of λ and theoretical TCT

From Figure 3, it shows that λ and theoretical TCT nearly have the same change tendency. So it proves that the real-time estimating method can forecast the change of TCT conveniently.

4 CONCLUSIONS

- According to the definition of gas utilization rate, a relationship between the gas utilization rate and the direct reduction rate is established. Then the effect of gas utilization rate on coke ratio is calculated based on the relationship between direct reduction rate and coke ratio. The coke ratio decreases about 4.5 kg·$(tHM)^{-1}$ while the gas utilization rate increases by 1%.
- According to the calculation model of the TCT, the effect of coke ratio on TCT is calculated. As the coke ratio decreases 1 kg·$(tHM)^{-1}$, the TCT decreases about 1.94 K.
- A new index which associates with gas utilization rate and coke ratio is proposed to predict the change tendency of TCT. The real-time estimating results of TCT are in good agreement with theoretical results. The proposed method to forecast TCT in present work is applicable to be used in practical production.

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