Research Article

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Furnace heat prediction and control model and its application to large blast furnace

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Abstract: Blast furnace heat is the key to the blast furnace's high efficiency and stable operation, and it is difficult to maintain a suitable temperature for large blast furnace operations. When designing the furnace heat prediction and control model, parameters with good reliability and measurability should be chosen to avoid using less accurate parameters and to ensure the accuracy and practicability of the model. This paper presents an effective model for large blast furnace temperature prediction and control. Using thermal equilibrium and the carbon-oxygen balance of the blast furnace's high-temperature zone, the slag-iron heat index was calculated. Using the relation between the molten iron temperature and slag-iron heat index, the furnace heat parameter can be calculated while production conditions are changed, which can guide furnace heat control.

Keywords: Furnace heat; Large blast furnace; Prediction and control; Thermal equilibrium; Carbon-oxygen balance

1 Introduction

Maintaining reasonable heat is the key to the blast furnace's high efficiency and stable operation. It is difficult to maintain suitable temperature for a large blast furnace, and temperatures that are too high or too low will not only cause blast furnace condition fluctuation, but also the production and technical indicators of the blast furnace and molten iron quality will be adversely affected. Because to the blast furnace production process is a complex reaction process involving high temperatures, external the factors

that influence furnace temperature, and long time lag for large blast furnace heat change, furnace temperature control is difficult [1–4].

With the improvement in equipment and technology in the large blast furnace, the accuracy of certain blast furnace process parameters has clearly improved. For example, the air leaking rate of most small blast furnaces before was more than 8%, but in the modern large blast furnace, it is usually less than 2%. Meanwhile, the required accuracy for furnace temperature control is also improved. When designing the furnace heat prediction and control model, good parameters should be chosen for reliability and to avoid using less accurate parameters to ensure the accuracy and practicality of the model. In order to satisfy the temperature requirements, the operators of blast furnaces should predict the furnace temperature correctly according to the operation parameters and accurate adjustment measures. This paper presents an effective method for large blast furnace temperature prediction and control, which can guide furnace heat adjustment.

There are many factors that influence blast furnace heat. The main factors are blast parameters (including blast volume, rich oxygen flow, PCI rate, blast humidity, and blast temperature), coke load, gas utilization, operation yield, quality of raw materials and fuel (including: coke, coal, sintering, and pellet), heat load, and furnace dust. The furnace heat parameters should be calculated when the above mentioned conditions are changed.

The calculation model presented in this paper are as follows. Firstly, recent data on blast furnace operation were collected, as the benchmark data for blast furnace operation. Secondly, the blast furnace benchmark data were used in the blast furnace high temperature thermal equilibrium and carbon-oxygen balance equations, the theoretical PCI rate was calculated, the theoretical direct reduction of carbon consumption under the benchmark conditions and slag-iron heat index was calculated. Thirdly, the blast furnace target parameters was used in the thermal equilibrium and carbon-oxygen balance equations for the blast furnace high-temperature zone, target slag-iron heat index was calculated, the relation between the temperature and slag-iron heat index was established, and the

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molten iron temperature and [Si] were calculated; Finally, corresponding to the target molten iron temperature, the slag-iron heat index was used in the blast furnace high temperature thermal equilibrium and carbon-oxygen balance equations, and the PCI rate and the quantity of coal needed were calculated, such that heat control could be achieved.

2 Calculation of the theoretical PCI rate

First, the benchmark parameters should be statistics that can represent the recent operating status of the blast furnace (the "0" on the right is marked as the benchmark parameter), and the statistical parameters are shown in Table 1.

Atmospheric humidity (%):

$$f^0 = \frac{22.4 \times H_{ATS}^0}{1000 \times 18} \quad (1)$$

Amount of O₂ per minute (Nm³/min):

$$O_{2_b}^0 = [0.21 \times (1 - f^0) + 0.5 \times f^0] \times V_b^0 + \frac{V_{coal}^0}{60} + \frac{\lambda_{O_2} \times V_{O_2}^0}{60} + \frac{1000 \times 22.4 \times H_{ADD}^0}{2 \times 18 \times 60} \quad (2)$$

where, λ_{O_2} is the quality percentage of O₂ in rich oxygen, which is 99.7%.

Oxygen consumption in combustion per ton iron (Nm³/tFe):

$$O_{CBT}^0 = \frac{1440 \times O_{2_b}^0}{P^0} \quad (3)$$

Carbon consumption in combustion per ton iron (kg/tFe):

$$C_{CBT}^0 = O_{CBT}^0 \times \frac{24}{22.4} \quad (4)$$

Under normal circumstances, the ratio of unburned coal powder to furnace dust is lower, and the influence on calculation of the thermal equilibrium and carbon-oxygen balance is not larger, but as the PCI rate increases, unburned coal powder into the furnace dust markedly increases, M₀ should be the quantity of coal that actually reacts in the furnace, which is the total quantity of coal minus the quantity of coal increased in the furnace dust. Assuming that the coal is burned completely in the tuyere zone, then carbon consumption of coke in combustion per ton iron (kg/tFe)

$$C_{CBT_coke}^0 = C_{CBT}^0 - M^0 \times \omega^0 C_{coal} / 100 \quad (5)$$

Amount of coke gasification per ton iron (kg/tFe):

$$C_{GAS_coke}^0 = K^0 \times \omega^0 (C_{coke}) / 100 - C_{CBR}^0 - C_{dust}^0 \quad (6)$$

Carbon consumption by direct reduction per ton iron (kg/tFe):

$$C_{dFe}^0 = C_{GAS_coke}^0 - C_{CBT_coke}^0 - C_{da}^0 \quad (7)$$

where C_{da}^0 represents carbon consumption of elements reduced other than iron (kg/tFe) and C_{CBR}^0 is the amount of carburizing in pig iron (kg/tFe). C_{dust}^0 is the carbon content in dust per ton iron (kg/tFe).

The amount of oxygen entering into the blast furnace gas from raw materials and fuel (kg/tFe) is

$$\begin{aligned} O_M^0 = & m_{sint}^0 \times [\omega^0 (Fe_2O_3_{sint}) / 100 \times 48 / 160 \\ & + \omega^0 (FeO_{sint}) / 100 \times 16 / 72] + m_{pell}^0 \\ & \times [\omega^0 (Fe_2O_3_{pell}) / 100 \times 48 / 160 + \omega^0 (FeO_{pell}) / 100 \\ & \times 16 / 72] - m_{dust}^0 \times [\omega^0 (Fe_2O_3_{dust}) / 100 \times 48 / 160 \\ & + \omega^0 (FeO_{dust}) / 100 \times 16 / 72] - m_{slag}^0 \times \omega^0 (FeO) / 100 \\ & \times 16 / 72 + M^0 \times [\omega^0 (H_2O_{coal}) / 100 / (1 \\ & - \omega^0 (H_2O_{coal}) / 100) / 18 \times 16 + \omega^0 (O_{coal}) / 100] + K^0 \\ & \times \omega^0 (O_{coke} / 100 + 10 \times ([Si]^0 \times 32 / 28 + [Mn]^0 \times 16 / 55 \\ & + [P]^0 \times 80 / 62) + m_{slag}^0 \times (S)^0 / 100 \times 16 / 32 \end{aligned} \quad (8)$$

Amount of moles H containing in per kg coal (kmol/kg):

$$\begin{aligned} n^0 (H_{coal}) = & [\omega^0 (H_{coal}) / 100 / 2 \\ & + \omega^0 (H_2O_{coal}) / 100 / (1 - \omega^0 (H_2O_{coal}) / 100) / 18] \end{aligned} \quad (9)$$

Use the above calculation results in the carbon-oxygen balance equation [5]:

$$\begin{aligned} \eta_{CO}^0 = & \frac{O_M^0 / 16 - C_{dFe}^0 / 12}{M^0 \times \omega^0 (C_{coal}) / 100 + C_{GAS_coke}^0 / 12} \\ & - \frac{\eta_{H_2} \times v_{H_2O_b}^0 \times C_{CBT}^0 / 22.4 + M^0 \times n^0 (H_{coal})}{M^0 \times \omega^0 (C_{coal}) / 100 + C_{GAS_coke}^0 / 12} \end{aligned} \quad (10)$$

The denominator is the total volume of carbon gas in moles, the numerator is the total volume of CO₂ gas in moles, and the amount is equal to the total amount of CO₂ generated from reaction of CO and O. CO comes from the tuyere combustion and O from raw materials and fuel, minus the mole amount of CO that derived from the direct reduction process of C and FeO, and minus the molar volume of H₂O that is derived from the direct reduction of H and O. η_{H_2} indicates the utilization ratio of hydrogen in the high temperature zone, which is generally 30%-50%.

Table 1: Benchmark parameters of blast furnace.

Item	Symbol	Units	Benchmark parameter
Blast volume	V_b	Nm^3/min	6096.00
Rich oxygen flow	V_{O_2}	Nm^3/h	15929.00
Atmospheric humidity	H_{ATS}	g/m^3	3.00
Humidification quantity	H_{ADD}	t/h	0.10
Blast temperature	BT	$^{\circ}\text{C}$	1267.00
Gas utilization ratio	η_{CO}	-	49.51%
Molten iron temperature	PT	$^{\circ}\text{C}$	1515.00
Coke rate	K	kg/tFe	326.56
PCI rate(dry)	M	kg/tFe	190.60
Yield of iron	P	t/d	9458.72
Heat load	Q_{load}	$10\text{MJ}/\text{h}$	8453.00
Carbon in coke	$\omega(C_{coke})$	%	87.29
Ash in coke	$\omega(A_{coke})$	%	11.67
Carbon in coal	$\omega(C_{coal})$	%	69.97
Ash in coal	$\omega(A_{coal})$	%	10.86
Consumption of sintering per ton iron	M_{sint}	kg/tFe	1213.30
Consumption of pellets per ton iron	M_{pell}	kg/tFe	391.11
[Si]	[Si]	%	0.42
[Fe]	[Fe]	%	94.72
[C]	[C]	%	4.70
[Mn]	[Mn]	%	0.04
[P]	[P]	%	0.07
[Ti]	[Ti]	%	0.03
Slag rate	M_{slag}	kg/tFe	305.00
Moisture in coal	$\omega(H_2O_{coal})$	%	1.32
O in coal	$\omega(O_{coal})$	%	8.21
Fe_2O_3 in Sintering	$\omega(\text{Fe}_2\text{O}_{3sint})$	%	72.44
FeO in Sintering	$\omega(\text{FeO}_{sint})$	%	9.59
Fe_2O_3 in pellets	$\omega(\text{Fe}_2\text{O}_{3pell})$	%	90.88
FeO in pellets	$\omega(\text{FeO}_{pell})$	%	0.66
FeO in Slag	(FeO)	%	0.04
S in Slag	(S)	%	1.02
Furnace dust production per ton iron	M_{dust}	kg/tFe	17.00
Fe_2O_3 in dust	$\omega(\text{Fe}_2\text{O}_{3dust})$	%	48.12
FeO in dust	$\omega(\text{FeO}_{dust})$	%	6.82
C in dust	$\omega(C_{dust})$	%	20.25
O in coke	$\omega(O_{coke})$	%	0.70
Blast volume by PC	V_{coal}	Nm^3/min	2873.00
Nitrogen volume by PC	$V_{coal_N_2}$	Nm^3/h	4000.00
Hydrogen utilization	η_{H_2}	-	40.00%

Transform equation (9) to be

$$M^0 = \frac{12 \times O_M^0 / 16 + C_{CBT}^0 + C_{da}^0}{(\eta_{CO}^0 + 1) \times \omega^0(C_{coal}) / 100 + 12 \times n^0(H_{coal})} \quad (11)$$

$$- \frac{(\eta_{CO}^0 + 1) \times C_{GAS_coke}^0 - 12 \times \eta_{H_2} \times v_{H_2O_b}^0 \times C_{CBT}^0 / 22.4}{(\eta_{CO}^0 + 1) \times \omega^0(C_{coal}) / 100 + 12 \times n^0(H_{coal})}$$

Use M^0 in equations (5) and (7), $C_{CBT_coke}^0$ and C_{dFe}^0 can be calculated.

Comparing the theoretical PCI rate calculated from the above equation with the actual coal, if the deviation is not large, it can be directly used in the next calculation. However, the calculated data need to be checked for mis-

takes or parameter distortion. Based on this premise, the deviation between theoretical and actual quantity of coal needed (or PCI rate) is adjusted to ensure the accuracy of the calculated results.

3 Calculation of slag-iron heat index [6–10]

Total volume of hot air coming into the blast furnace per minute (Nm^3/min):

$$V_{HA}^0 = V_b^0 + V_{O_2}^0/60 + V_{coal}^0/60 + V_{coal_N_2}^0/60 + H_{ADD}^0 \times 1000 \times 22.4/18/60 \quad (12)$$

The ratio of H_2O in hot air:

$$\phi^0(\text{H}_2\text{O}) = (H_{ADD}^0 \times 1000000/60 + (V_b^0 + V_{coal}^0/60) \times H_{ATS}^0) \times 22.4/18/1000/V_b^0 \quad (13)$$

The ratio of O_2 in hot air after the decomposition of H_2O :

$$\phi_1^0(\text{O}_2) = [(0.21 + 0.29 \times H_{ATS}^0 \times 22.4/18/1000) \times (V_b^0 + V_{coal}^0/60) + V_{O_2}^0/60 \times \lambda_{O_2} + H_{ADD}^0 \times 1000 \times 22.4/18/2/60]/V_b^0 \quad (14)$$

The ratio of O_2 in hot air before the decomposition of H_2O :

$$\phi_2^0(\text{O}_2) = \phi_1^0(\text{O}_2) - \phi^0(\text{H}_2\text{O})/2 \quad (15)$$

The ratio of N_2 in hot air:

$$\phi^0(\text{N}_2) = 1 - \phi_2^0(\text{O}_2) - \phi^0(\text{H}_2\text{O}) \quad (16)$$

The volume of hot air needed to burn per kilogram carbon (Nm^3/kg):

$$v_{HA}^0 = 22.4/24/\phi_1^0(\text{O}_2) \quad (17)$$

The volume of H_2O in hot air to burn per kilogram carbon (Nm^3/kg):

$$v_{H_2O_HA}^0 = v_{HA}^0 \times \phi^0(\text{H}_2\text{O}) \quad (18)$$

The volume of O_2 in hot air to burn per kilogram carbon (Nm^3/kg):

$$v_{O_2_HA}^0 = v_{HA}^0 \times \phi_2^0(\text{O}_2) \quad (19)$$

The volume of N_2 in hot air to burn per kilogram carbon (Nm^3/kg):

$$v_{N_2_HA}^0 = v_{HA}^0 \times \phi^0(\text{N}_2) \quad (20)$$

The volume of CO generated by burning per kilogram carbon (Nm^3/kg):

$$v_{CO_GAS}^0 = 22.4/12 \quad (21)$$

The volume of N_2 generated by burning per kilogram carbon (Nm^3/kg):

$$v_{N_2_GAS}^0 = v_{N_2_HB}^0 \quad (22)$$

The volume of H_2 generated by burning per kilogram carbon (Nm^3/kg):

$$v_{H_2_GAS}^0 = 22.4/24/\phi_1^0(\text{O}_2) \times \phi^0(\text{H}_2\text{O}) \times (1 - \eta_{H_2}) \quad (23)$$

The volume of H_2O generated by burning per kilogram carbon (Nm^3/kg):

$$v_{H_2O_GAS}^0 = 22.4/24/\phi_1^0(\text{O}_2) \times \phi^0(\text{H}_2\text{O}) \times \eta_{H_2} \quad (24)$$

Thermal revenue by burning per kilogram carbon in high-temperature zone (kJ/kg (C)):

$$\begin{aligned} q_{C_CBT}^0 = & 9800 + (q_{CO_HA}^0 \times v_{CO_HA}^0 + q_{N_2_HA}^0 \times v_{N_2_HA}^0 + q_{H_2O_HA}^0 \times v_{H_2O_HA}^0) - 10785 \times v_{H_2O_HA}^0 \\ & - q_{H_RDC} \times \eta_{H_2} \times v_{H_2_GAS}^0 - (q_{CO_GAS}^0 \times v_{CO_GAS}^0 + q_{N_2_GAS}^0 \times v_{N_2_GAS}^0 + q_{H_2O_GAS}^0 \times v_{H_2O_GAS}^0 + q_{H_2_GAS}^0 \times v_{H_2_GAS}^0) \end{aligned} \quad (25)$$

where, $q_{x_HB}^0$ indicate the heat enthalpy of x gas at s specific under blast temperature, and $q_{x_GAS}^0$ represents the heat enthalpy of x gas at the limit temperature (950°C). The heat enthalpy calculation uses the method mentioned in the literature [6]. q_{H_RDC} is the thermal consumption of hydrogen reduced per kmol.

While burning coke, thermal revenue burning per kilogram carbon (kJ/kg (C)) is

$$q_{C_CBT_coke}^0 = q_{C_CBT}^0 - \bar{C}_{coke} \times \frac{\omega^0 A_{coke}}{\omega^0 C_{coke}} \times (t_{slag} - t_{limit}) \quad (26)$$

While burning coal, thermal revenue burning per kilogram coal (kJ/kg (C)) is

$$q_{coal}^0 = q_{C_CBT}^0 \times \omega^0(C_{coal})/100 - q_{H_RDC} \times \eta_{H_2} \times n^0(H_{coal}) - q_{DEC} \quad (27)$$

Thermal consumption of carbon per kilogram directly reduced (kJ/kg (C)) is

$$q_{dFe}^0 = q_{dFe_RDC}^0 + \bar{C}_{coke} \times \frac{\omega^0 A_{coke}}{\omega^0 C_{coke}} \times (t_{slag} - t_{limit}) \quad (28)$$

Heat loss per ton iron (kJ/tFe):

$$Q_{loss}^0 = \lambda_{loss} \times Q_{load} \times 10000 \times 24/P^0 \quad (29)$$

Using the above calculation results in the thermal equilibrium and carbon-oxygen balance equations to calculate the blast furnace high-temperature zone, the target slag-iron heat index (kJ/tFe) is

$$Q_{\text{heat}}^0 = q_{C_CBT}^0 \times C_{CBT_coke}^0 + q_{\text{coal}}^0 \times M^0 - q_{dFe}^0 \times C_{dFe}^0 - Q_{\text{loss}}^0 \quad (30)$$

The slag-iron heat index indicates the heat of iron and slag per ton of iron, which represent the heat level of the blast furnace. The higher the slag-iron heat index is, the higher the furnace heat is.

4 Furnace heat prediction and control

Using the target parameters (or actual running parameters) in the thermal equilibrium and carbon-oxygen balance equations,

$$\lambda_{\text{heat}} \times Q_{\text{heat}}^0 = q_{C_CBT} \times C_{CBT_coke} + q_{\text{coal}} \times M - q_{dFe} \times C_{dFe} - Q_{\text{loss}} \quad (31)$$

$$\eta_{CO} = \frac{O_M/16 - C_{dFe}/12}{M \times \omega(C_{\text{coal}})/100 + C_{GAS_coke}/12} - \frac{\eta_{H_2} \times v_{H_2O_b} \times C_{CBT}/22.4 + M \times n(H_{\text{coal}})}{M \times \omega(C_{\text{coal}})/100 + C_{GAS_coke}/12} \quad (32)$$

where,

$$C_{GAS_coke} = K \times \omega(C_{\text{coke}})/100 - C_{CBR} - C_{\text{dust}} \quad (33)$$

$$C_{CBT_coke} = C_{GAS_coke} - C_{dFe} - C_{da} \quad (34)$$

$$C_{CBT} = C_{CBT_coke} + M \times \omega(C_{\text{coal}})/100 \quad (35)$$

$$C_{CBT} = C_{GAS_coke} - C_{dFe} - C_{da} + M \times \omega(C_{\text{coal}})/100 \quad (36)$$

The calculation method of O_M , C_{da} , C_{CBR} , C_{dust} , $n(H_{\text{coal}})$, q_{C_CBT} , q_{coal} , q_{dFe} is the same as O_M^0 , C_{da}^0 , C_{CBR}^0 , C_{dust}^0 , $n^0(H_{\text{coal}})$, $q_{C_CBT}^0$, q_{coal}^0 , q_{dFe}^0 .

$Q_{\text{heat}} = \lambda_{\text{heat}} \times Q_{\text{heat}}^0$, λ_{heat} is heat coefficient, and when $\lambda_{\text{heat}} = 1$, furnace heat can be considered equivalent to the benchmark furnace heat.

The formula of molten iron temperature prediction:

$$T_{\text{iron}} = [1 + \alpha \times \lambda_{\text{heat}} - 1] \times T_{\text{iron}}^0 \quad (37)$$

where, α is the correlation coefficient between molten iron temperature and slag-iron heat index.

Using the above calculation results in equations (31) and (32), only M and C_{dFe} are the two unknowns in the equation [5].

$$q_{\text{coal}} \times M + (q_{dFe} - q_{C_CBT}) \times C_{dFe} = \lambda_{\text{heat}} \times Q_{\text{heat}}^0 - q_{C_CBT} \times (C_{GAS_coke} - C_{da}) + Q_{\text{loss}} \quad (38)$$

$$\left[\frac{\eta_{CO} \times \omega(C_{\text{coal}})/100}{12} + \eta_{H_2} \times \left(\frac{v_{H_2O_HB} \times \omega(C_{\text{coal}})/100}{22.4} + n(H_{\text{coal}}) \right) \right] \times M + \left(\frac{1}{12} + \frac{\eta_{H_2} \times v_{H_2O_HB}}{22.4} \right) \times C_{dFe} = \frac{O_M}{16} - \frac{\eta_{H_2} \times v_{H_2O_HB} \times (C_{GAS_coke} - C_{da})}{22.4} - \frac{\eta_{CO} \times C_{GAS_coke}}{12} \quad (39)$$

M and C_{dFe} can be obtained from equations (38) and (39), and the result can be use in equations (34) and (35) to calculate C_{CBT_coke} and C_{CBT} .

The estimated daily output of molten iron (t/d):

$$P = \frac{1440 \times O_{2_HB}}{C_{CBT} \times 22.4/24} \quad (40)$$

The quantity of coal needed (t/h):

$$m_{\text{coal}} = P \times [M + (M^a - M^0)]/1 - \omega(H_2O_{\text{coal}})/100/1000/24 \quad (41)$$

5 Application of blast furnace heat control

Using the benchmark parameters of Table 1 in the above calculation equation, the calculation results are shown in Table 2.

According to the calculations in the above section, while the operation parameters of the blast furnace are changed to maintain constant furnace heat, the quantity of the coal needed or other control parameters can be calculated.

In actual production, to stabilize the furnace conditions and heat, the operating parameters are often kept constant, but η_{CO} changes frequently. Through the above section, the estimated fuel rate and quantity of coal needed can be calculated for different η_{CO} , and the calculation results as shown in Figure 1.

When the heat of blast furnace needs to be adjusted, assuming that only the quantity of coal is adjusted, other operating parameters remain the same, and at the same

Table 2: Heat calculation results of blast furnace.

Item	Symbol	Units	Results
Atmospheric humidity	f	-	0.37%
Ratio of O_2 in hot air	O_{2_HB}	Nm^3/min	1562.59
Oxygen consumption in combustion per ton iron	O_{CBT}	Nm^3/tFe	237.89
Carbon consumption in combustion per ton iron	C_{CBT}	kg/tFe	254.88
Amount of coke gasification per ton iron	C_{GAS_coke}	kg/tFe	234.60
Amount of oxygen entering blast furnace gas from raw materials and fuel	O_M	kg/tFe	421.52
Amount of moles H in per kilogram coal	$N(H_{coal})$	$kmol/kg$	0.018
PCI rate	M	kg/tFe	184.72
Oxygen consumption in combustion per ton iron	C_{CBT_coke}	kg/tFe	123.35
Carbon consumption by direct reduction per ton iron	C_{dFe}	kg/tFe	105.65
Total volume of hot air coming into the blast furnace per minute	V_{HB}	Nm^3/min	6748.11
Ratio of H_2O in hot air	$\varphi(H_2O)$	-	0.39%
Ratio of O_2 in hot air after the decomposition of H_2O	$\varphi_1(O_2)$	-	24.12%
Ratio of O_2 in hot air after the decomposition of H_2O	$\varphi_2(O_2)$	-	23.93%
Ratio of N_2 in hot air	$\varphi(N_2)$	-	75.69%
Volume of hot air needed to burn per kilogram carbon	N_{HB}	Nm^3/kg	3.87
Volume of H_2O in hot air to burn per kilogram carbon	$v_{H_2O_HB}$	Nm^3/kg	0.015
Volume of O_2 in hot air to burn per kilogram carbon	$v_{O_2_HB}$	Nm^3/kg	0.93
Volume of N_2 in hot air to burn per kilogram carbon	$v_{N_2_HB}$	Nm^3/kg	2.93
Volume of CO generated by burning per kilogram carbon	v_{CO_GAS}	Nm^3/kg	1.87
Volume of N_2 generated by burning per kilogram carbon	$v_{N_2_GAS}$	Nm^3/kg	2.93
Volume of H_2 generated by burning per kilogram carbon	$v_{H_2_GAS}$	Nm^3/kg	0.009
Volume of H_2O generated by burning per kilogram carbon	$v_{H_2O_GAS}$	Nm^3/kg	0.006
Thermal revenue by burning per kilogram carbon in high-temperature zone	q_{C_CBT}	$kJ/kg(C)$	10308.33
Thermal revenue by burning per kilogram carbon while burning coke	$q_{C_CBT_coke}$	$kJ/kg(C)$	10223.32
Thermal revenue by burning per kilogram coal while burning coal	q_{coal}	kJ/kg	6561.37
Thermal consumption of per kilogram carbon directly reduced	q_{dFe}	$kJ/kg(C)$	12746.92
Heat loss per ton iron	Q_{loss}	kJ/tFe	214481.47
Slag-iron heat index	Q_{heat}	kJ/tFe	720564

Table 3: Amount of coal needed when the operating parameters of the blast furnace are changed.

Item	Units	Operating parameters changed	Amount of coal needed (t/h)
Blast volume	Nm^3/min	+100	+1.03
Rich oxygen flow	Nm^3/h	+1000	+0.82
Atmospheric humidity	g/m^3	+10	+0.50
Humidification quantity	t/h	+1	+0.35
Coke rate	kg/tFe	+10	-4.27

time direct reduction of heat consumption is constant. Therefore, simultaneous equations (37), (38) and (39), with such parameters as estimated fuel rate, quantity of coal needed, estimated yield and η_{CO} can be obtained for different temperatures, and the calculation results are shown in Figure 2 and Figure 3.

The furnace heat prediction model can be used to calculate the temperature of molten iron while the operation parameters of blast volume, η_{CO} , and operation yield change simultaneously. The slag-iron heat index, which is 693976 kJ/tFe, can be calculated for the following conditions: blast volume is 6196 Nm^3/min , rich oxygen flow is

Figure 1: Estimated fuel rate and quantity of coal needed on different η_{CO}

Figure 2: Estimated fuel rate and quantity of coal needed at different temperature.

Figure 3: Estimated yield and η_{CO} at different temperature.

16929 Nm³/min, atmospheric humidity is 13.00 g/m³, humidification quantity is 1.10 t/h, η_{CO} is 50.51%, coke rate is 336.56 kg/tFe, operation yield is 9558.72 t/d, and estimated molten iron temperature is 1507°C.

By adopting the furnace heat prediction and control model, the qualified rate of hot metal temperature in a TISCO large blast furnace ($T = 1495 \sim 1515^\circ\text{C}$) increased from 60.5% to 76.7%, and the qualified rate of [Si] in hot metal (the ratio of [Si] in hot metal < 0.55%) increased from 62.9% to 68.7%, which were good results.

6 Summary

When designing the furnace heat prediction and control model, parameters with good reliability to should be chosen, to avoid using less accurate parameters and to ensure the accuracy and practicality of the model. This paper presents an effective method for blast furnace temperature prediction and control.

1. The primary factors that influence blast furnace heat include blast parameters, coke load, gas utilization ratio, operation yield, quality of raw materials and fuel, heat load, and furnace dust. Using the furnace heat control model proposed in this paper, furnace heat parameters can be calculated when the above mentioned conditions are changed.
2. By using the thermal equilibrium and carbon-oxygen balance equation for the blast furnace high-temperature zone, the slag-iron heat index which represent the heat level of the blast furnace can be calculated.
3. Using the relation between the molten iron temperature and slag-iron heat index, the furnace heat parameters can be calculated when production conditions are changed, which can guide furnace heat control.

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