Research Article

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Study on the Appropriate Production Parameters of a Gas-injection Blast Furnace

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Abstract: The change regulations of the smelting parameters in a gas-injection blast furnace are investigated using theoretical calculations. The results show that when the volume of gas injected, the oxygen enrichment rate and the theoretical combustion temperature of tuyere are $600 \text{ m}^3/\text{tHM}$, 10% and $1950\sim 2200^\circ\text{C}$, respectively, the conditions meet the smelting requirements of a blast furnace. With the increase of the oxygen enrichment rate, the required air volume decreases, the contents of CO and H_2 in the top gas increase, and the content of CO_2 first increases and then decreases. With an increase of the volume of gas injected, the coke rate decreases. In addition, when the oxygen enrichment rate and the volume of gas injected are 10% and $600 \text{ m}^3/\text{tHM}$, respectively, the CO content of the top gas constantly increases with the increase of the coke rate, while the H_2 and CO_2 contents both decrease. With the increase of the H_2 content in the gas, the direct reduction degree of iron gradually decreases and the volume shrinkage burden increases. Apparently, injecting gas into the blast furnace can prevent the theoretical combustion temperature from being too high and solve the contradiction between the upper cooling and lower heating of the blast furnace.

Keywords: Blast furnace; Gas injection; Manufacturing parameter

1 Introduction

Iron and steel enterprises compose one of the main energy consumption and greenhouse gas emission industries, and the CO_2 emissions directly related to the iron-making process are over 90% [1, 2]. Pulverized coal injection is one of the important measures taken for energy saving and emissions reduction in blast furnaces. However, a large amount of pulverized coal being injected will cause many adverse effects on BF smelting [3–7]. For example, pulverized coal injected into the blast furnace internally will undergo a series of physical and chemical changes that include heating, decomposition, combustion, and slagging. As a result, the reaction in the tuyere will become complicated, and the operation will be difficult. With an increase in the volume of pulverized coal injected, the softening-melting zone enlarges, and the coke is seriously damaged. As a result, the quality of the coke restricts the volume of pulverized coal injected. The increase of the pulverized coal volume will also inevitably lead to the increase of unburnt pulverized coal, which will further deteriorate the working state of the softening-melting zone and the slagging zone. A large amount of ash is produced by the combustion of coke and pulverized coal in the tuyere of a blast furnace, and it participates in slag-making in the hearth, which causes the basicity of the primary slag to be high and the compositions of the final slag and primary slag to fluctuate greatly. Oxygen enrichment and pulverized coal injection lead to the heat distribution of the blast furnace differentiating into "upper cooling" and "lower heating", and as a result, some measures have to be taken to meet the requirement of heating in the upper part of the blast furnace. In addition, CO_2 emissions are out of control. Consequently, a new process in which oxygen and gas both are injected into the blast furnace has been developed [8, 9]. The most important characteristic of this process is that the combustion of pulverized coal in the blast furnace tuyere is moved into the gasifier, and the BF top gas is also injected into the gasifier. Finally, the gas produced is injected into the blast furnace. This new process can overcome the defects of the PCI and increase the H_2 content of the blast furnace bosh gas [10, 11]; there-

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fore, it has strong advantages in some aspects that include the production efficiency, environmental protection, economic benefits, etc. [12, 13]. The technological process is shown in Figure 1. In this paper, through the comparison of the smelting effects between the new process and the conventional blast furnace process, the operating characteristics and advantages of the new process are obtained.

1 blast furnace; 2 gas-making furnace; 3 pressure device; 4 gas heating device

Figure 1: GOBF blast furnace process

2 Establishment of the mathematical model for a gas-injection blast furnace

Based on the actual reaction in a conventional blast furnace and the balanced calculations of material and heat, a model of the new process using the components of raw materials and actual operating parameters is established, which provides a foundation for research of the new process and the determination of the optimal parameters. It is proposed that this model can accurately reflect the changes of the composition and temperature of the blast furnace after the gas passes through the gasifier and into the blast furnace, determine the effect laws of different factors affecting the operation of the blast furnace, and address whether different parameters can meet the operating stability of the whole blast furnace. Therefore, the rational application of this model has important meaning in the study of the new process.

2.1 Material balance

The material balance of the blast furnace is divided into two parts, income and expenditure, including the calculation of the slag amount, the calculation of the air volume, the calculation of the volume of the top gas, etc. The calculation of the material balance is helpful in the comprehensive and quantitative analysis and the in-depth study of the blast furnace process, as well as in preparing for the calculation of the heat balance.

2.1.1 Calculation of the slag amount

The calculation of the slag amount is based on the raw materials used in the blast furnace, which are applied to determine the composition and quantity of the blast furnace slag, including MgO , CaO , MnO and other components. The algorithm is shown in formula 1.

$$m(X) = \sum \text{the amount of various raw materials} \times X_i \quad (1)$$

In the formula, X_i represents $CaO_{(i)}$, $MgO_{(i)}$, $SiO_{2(i)}$, $Al_2O_{3(i)}$, $MnO_{(i)}$ and $S_{(i)}$, which are the contents of the corresponding components in each furnace burden. The unit of $m(X)$ is kg.

2.1.2 Calculation of the air volume

The calculation of the air volume is the basis of the balanced calculation of the blast furnace burden, which is of guiding significance in the calculation of the next step of the top gas. The blast volume of per ton of iron is determined by the amount of carbon involved in combustion in the front of the tuyere and the amount of oxygen in the blast.

2.1.2.1 Amount of combustion carbon in the front of the tuyere

There are many factors that influence the combustion carbon content in the front of the tuyere. It is determined by the calculation of the three parameters of the oxidation carbon content, the reductive carbon content of the alloy elements, and the carbon consumption due to the direct reduction of iron. Each part has a great influence on the final result of the calculation. The algorithm is shown in formula 2.

$$C_b = C_O - C_{da} - C_{dFe} \quad (2)$$

In the formula, C_b , C_O , C_{da} and C_{dFe} represent the carbon amount in the tuyere, the oxidation carbon content,

the reductive carbon content of the alloy elements and the carbon consumption due to the direct reduction of iron, respectively. The unit of C_b is kg/tFe^{-1} .

1. Calculation of the oxidation carbon content C_O

The oxidation carbon content includes the coke, pulverized coal (there is no coal injection in the new process, so it does not need to be considered), carbon content in the pig iron and carbon consumption of the CH_4 generated. The algorithm is shown in formula 3.

$$C_O = C_f - C_C - C_{\text{CH}_4} \quad (3)$$

In the formula, C_f , C_C and C_{CH_4} represent the carbon consumption of coke and pulverized coal, the carbon content in the pig iron, and the carbon consumption of the CH_4 generated, respectively.

2. Calculation of the reductive carbon content C_{da} of alloy elements

The reductive carbon content of alloy elements includes the reductive carbon consumption of elements in the pig iron, the reductive carbon consumption of CO_2 in the limestone and the carbon consumption of desulphurization. The algorithm is shown in formula 4.

$$C_{da} = C_{\text{element}} + C_{\text{limestone}} + C_S \quad (4)$$

In the formula, C_{element} , $C_{\text{limestone}}$ and C_S represent the reductive carbon consumption of elements in the pig iron, the reductive carbon consumption of CO_2 in the limestone and the carbon consumption of desulphurization, respectively.

3. Calculation of the carbon consumption C_{dFe} in direct reduction

The carbon consumption in direct reduction is the amount of carbon needed to smelt one ton of pig iron, and it has a great relationship with the direct reduction degree. The algorithm is shown in formula 5.

$$C_{\text{dFe}} = 12 \times \text{Fe.r} \times r_d / 56 \quad (5)$$

In the formula, Fe.r is the amount of reduced iron in the blast furnace smelting the ton of iron, which is generally $10[\text{Fe}]$, and r_d is the direct reduction degree.

2.1.2.2 Oxygen content in the blast (the unit is a percentage)

The modern blast furnace is in continuous pursuit of a high oxygen enrichment rate to reduce the coke rate, therefore, the changes of the oxygen content in the blast also have

a great influence on the calculation of the air volume and heat. The algorithm is shown in formula 6.

$$O_{2b} = 0.21 + 0.29 \times \varphi + (a - 0.21) \times W \quad (6)$$

In the formula, φ is the blast humidity, W is the amount of enriched oxygen per cubic meter in the blast, a is the purity of oxygen in the enriched oxygen, and $(a - 0.21) \times W$ is the oxygen enrichment rate.

1. Blast volume the unit is $\text{m}^3/\text{tFe}^{-1}$:

According to the chemical reaction in the raceway in the front of the tuyere in the blast furnace, the blast volume required for one ton of iron is calculated. The algorithm is shown in formula 7.

$$V_b = \frac{22.4 \times C_b}{24 \times O_{2b}} = 0.933 \times C_b / O_{2b} \quad (7)$$

2.1.3 Volume of the top gas (the unit is $\text{m}^3/\text{tFe}^{-1}$)

The top gas of the blast furnace is composed of six kinds of gas, including CO_2 , CO , N_2 , H_2 , H_2O and CH_4 , and the quantity of each gas is influenced by many factors. The injection of the gas made by coal is used in the new process, which has a great influence on the top gas of the furnace compared with that in the traditional technology.

2.1.3.1 CH_4

There is not a high content of CH_4 in the top gas. It has three main sources, including the gas injection, the volatile matter of coke and the carbon and hydrogen synthesis. The algorithm is shown in formula 8.

$$V_{\text{CH}_4} = K \times \text{CH}_{4\text{coke}} \times 22.4/16 + V_{\text{injectingCH}_4} + 22.4C_{\text{CH}_4}/12 \quad (8)$$

In the formula, $\text{CH}_{4\text{coke}}$ is the content of methane in the coke and $V_{\text{injectingCH}_4}$ is the content of methane in the gas injection.

2.1.3.2 H_2

The hydrogen in the blast furnace is from four sources—the fuel, the blast humidity, and the crystalline water of the raw materials and coal gas injected—and the portion involved in the reduction and the production of CH_4 is consumed, while the rest enters the top gas. Due to the coal gas being injected in the new process, to a certain extent, the amount of hydrogen gas in the furnace is increased, which has a great influence on the reduction of the blast furnace.

The calculation of the content of H_2 in the top gas is shown in formula 9.

$$V_{H_2} = \sum H_2 - H_2 r - H_{2CH_4} \quad (9)$$

In the formula, $\sum H_2$ is the total hydrogen content entering the blast furnace, $H_2 r$ is the amount of hydrogen involved in the reduction according to the utilization rate of hydrogen, and H_{2CH_4} is the hydrogen content of the produced CH_4 .

2.1.3.3 H_2O

The content of H_2O is lower in the top gas, and it which mainly comes from two sources: hydrogen reduction and the furnace burden. The algorithm is shown in formula 10.

$$V_{H_2O} = \sum H_2 O + H_2 r \quad (10)$$

In the formula, $\sum H_2 O$ is the total water brought by the furnace burden.

2.1.3.4 CO_2

The CO_2 in the blast furnace is contributed from two sources: indirect reduction and the furnace burden, and the former is the main source. The indirect reduction of CO_2 is produced by the reduction of iron and manganese oxides in the raw materials. The CO_2 brought by the furnace burden includes the flux, the CO_2 in the coke and the decomposition of limestone at high temperatures. The algorithm is shown in formula 11.

$$V_{CO_2} = V_{CO_{2indirectreduction}} + V_{CO_{2furnaceburden}} \quad (11)$$

In the formula, $V_{CO_{2indirectreduction}}$ is the amount of CO_2 produced by indirect reduction and $V_{CO_{2furnaceburden}}$ is the amount of CO_2 brought by the furnace burden.

2.1.3.5 CO

CO is the main reducing gas of the blast furnace, which plays an important role in the reduction of raw materials. The CO in the blast furnace is composed of four sources: the coal gas injected, the volatile matter of coke, oxides reduction and the combustion of carbon in the front of the tuyere. CO is combined with raw materials during the process of rising in the blast furnace, and it participates in indirect reduction reactions, which consume an amount of CO . The hydrogen content is increased, the direct reduction of the blast furnace is changed, and the coke rate is reduced during the process of injecting the gas made by

coal, which has a great influence on the content of CO in the top gas. The algorithm is shown in formula 12.

$$V_{CO} = V_{CO\ tuyere} + V_{CO\ reduction} + V_{CO\ coke} + V_{CO\ injecting} - V_{CO_2\ indirect\ reduction} \quad (12)$$

In the formula, $V_{CO\ tuyere}$, $V_{CO\ reduction}$, $V_{CO\ coke}$ and $V_{CO\ injecting}$ represent the amount of CO produced by the combustion of carbon in the front of the tuyere, the amount of CO produced by oxide reductions, the amount of CO in coke volatilization and the amount of CO in the coal gas injected, respectively.

2.1.3.6 N_2

N_2 is an inert gas, which is relatively stable in the blast furnace and does not participate in any reaction. It is mainly contributed by the blast, coke and coal gas injected. The algorithm is shown in formula 13.

$$V_{N_2} = V_{N_2\ blast} + V_{N_2\ coke} + V_{N_2\ injecting} \quad (13)$$

In the formula, $V_{N_2\ blast}$ is the amount of N_2 brought by the blast, $V_{N_2\ coke}$ is the amount of N_2 brought by the coke, and $V_{N_2\ injecting}$ is the amount of N_2 brought by the coal gas injected.

The top gas volume is the sum of each component of the six gases, and the algorithm is shown in formula 14.

$$V_g = V_{CO} + V_{CO_2} + V_{CH_4} + V_{H_2} + V_{N_2} + V_{H_2O} \quad (14)$$

2.1.4 Material balance sheet compilation

According to the results, the two parts of the material income and expenditure are listed. The relative error is calculated to verify the reasonableness of the calculation results. The error algorithm is shown in formula 15.

$$\text{Absolute error} = \text{Total quality of material income} \quad (15)$$

$$- \text{Total quality of material expenditure}$$

$$\text{Relative error} = \frac{\text{Absolute error}}{\text{Total material income}} \times 100\%$$

2.2 Heat balance

The blast furnace heat is divided into income and expenditure parts. The heat income includes the combustion heat of carbon in the front of the tuyere, the physical heat of the blast, the generated heat of CH_4 , the heat of slag formation, the physical heat of the furnace burden, etc.

The heat expenditure includes the heat consumption of oxide decomposition, the heat consumption of desulphurization, the heat consumption of carbonate decomposition, the heat consumption of water decomposition and evaporation, the heat taken away by molten iron, slag and top gas, the heat loss, etc. The unit is $\text{kJ} \cdot \text{t}^{-1}$.

2.2.1 Heat income

2.2.1.1 Calculation of the combustion heat of carbon in the front of the tuyere

The combustion heat of carbon in the front of the tuyere is an important source of heat in the blast furnace, and the heat is mainly produced by the combustion of coke and fuel injection in this area. The coal gas injected serves as alternative to pulverized coal in the new process, and the production of heat is reduced. The algorithm is shown in formula 16.

$$Q_c = 9781.2 \times C_b \quad (16)$$

In the formula, Q_c is the combustion heat of carbon in the front of the tuyere.

2.2.1.2 Physical heat of the blast

The physical heat of the blast is another important item in the heat income of the blast furnace, which is brought into the blast furnace during blasting, and the heat of the coal gas injected is also included in the new process. In addition, the wind temperature, the air volume and the humidity have a great influence on the physical heat of the blast. The algorithm is shown in formula 17.

$$Q_{wind} = V_b \times \{(1 - \varphi) \times q_b + \varphi \times q_{H_2O}\} + \sum V_{airinjection} \times q_{airinjection} \quad (17)$$

In the formula, φ is the blast humidity and q_{H_2O} and $q_{airinjection}$ represent the enthalpy of air, water and gas at the temperature of injection, respectively.

2.2.1.3 Generation heat of CH_4

The generation heat of CH_4 is produced by the exothermic binding of carbon and hydrogen, but the amount of CH_4 is lower, and its heat is not high. The algorithm is shown in formula 18.

$$Q_{\text{CH}_4} = 4.18 \times 803 \times 22.4 C_{\text{CH}_4} / 12 \quad (18)$$

2.2.1.4 Heat of slag formation

The heat of slag formation refers to the amount of heat released from the blast furnace slag, which is generated by the combination of alkaline oxides and acids in the raw material during the blast furnace smelting process. The heat of slag formation is a small part of the total heat income, and the CaO and MgO contained in the flux and the raw ore are mainly considered. The algorithm is shown in formula 19.

$$Q_{\text{slag}} = 4.18 \times 270 \times \{MgO + CaO\} \quad (19)$$

In the formula, $\{MgO + CaO\}$ is the total amount of CaO and MgO brought from the flux and the raw ore during the smelting process.

2.2.1.5 Physical heat of the furnace burden

The physical heat of the furnace burden is the heat taken away when the raw material enters the blast furnace; however, the modern blast furnace mostly uses cold material directly in the furnace, and the heat is relatively lower. The algorithm is shown in formula 20.

$$Q_{\text{Furnace burden}} = G_{\text{Furnace burden}} \times 25 \times 0.6897 \quad (20)$$

In the formula, $G_{\text{Furnace burden}}$ is the total amount of raw materials entering the blast furnace.

2.2.2 Heat expenditure

2.2.2.1 Heat consumption of oxides decomposition

The heat consumption of oxides decomposition is composed of four parts: the heat consumption of iron oxides reduction, the heat consumption of manganese oxides decomposition, the heat consumption of silicon oxides decomposition and the heat consumption of phosphorus reduction. Among them, the heat consumption of iron oxides reduction is more complex. According to the different morphologies and reduction processes of iron oxides, the heat consumption of ferric silicate decomposing into FeO, the heat consumption of Fe_3O_4 being reduced to FeO, the heat consumption of Fe_2O_3 being reduced to FeO, the heat consumption of FeO being reduced by H_2 , the heat consumption of FeO being reduced by C and the heat consumption of FeO being reduced by CO are calculated, respectively. The algorithm is shown in formula 21.

$$Q_{\text{oxidation}} = Q_{\text{dFe1}} + Q_{\text{dFe2}} + Q_{\text{dFe3}} + Q_{\text{dFe4}} + Q_{\text{dFe5}} + Q_{\text{dFe6}} + Q_{\text{dMn}} + Q_{\text{dSi}} + Q_{\text{dP}} \quad (21)$$

In the formula, Q_{dFe1} is the heat consumption of ferrous silicate decomposing into FeO, Q_{dFe2} is the heat consumption of Fe_3O_4 being reduced to FeO, Q_{dFe3} is the heat consumption of Fe_2O_3 being reduced to FeO, Q_{dFe4} is the heat consumption of FeO being reduced by H_2 , Q_{dFe5} is the heat consumption of FeO being reduced by C, Q_{dFe6} is the heat consumption of FeO being reduced by CO, Q_{dMn} is the heat consumption of manganese oxides decomposition, Q_{dSi} is the heat consumption of silicon oxides decomposition, and Q_{dp} is the heat consumption of phosphorus reduction.

2.2.2.2 Heat consumption of desulphurization

The sulfur in the blast furnace is mainly derived from the decomposition of the fuel, and the sulfur is removed from the slag by reaction with CaO. The algorithm is shown in formula 22.

$$Q_{desulfuration} = 4.18 \times 1139 \times S_{slag} \quad (22)$$

In the formula, $Q_{desulfuration}$ is the heat consumption of desulphurization and S_{slag} is the sulfur content in the slag produced by smelting the ton of iron.

2.2.2.3 Heat consumption of carbonate decomposition

The carbonates in the blast furnace mainly include two parts, magnesium carbonate and calcium carbonate, which decompose and absorb a large amount of heat. In addition, the calcium carbonate decomposes into CO_2 at high temperatures, and CO_2 will combine with carbon to produce carbonous loss reactions in the blast furnace, which consume a certain amount of heat. To simplify the calculation, the limestone decomposition rate is determined to be 50%. The algorithm is shown in formula 23.

$$Q_{decomposition} = Q_{shs} + Q_{tsm} + Q_{rs} \quad (23)$$

In the formula, Q_{shs} , Q_{tsm} and Q_{rs} represent the heat consumption of calcium carbonate decomposition, the heat consumption of magnesium carbonate decomposition and the heat consumption of carbon loss reactions, respectively.

2.2.2.4 Heat consumption of water decomposition and evaporation

The water in the blast furnace consists of two parts: the moisture brought by the furnace burden and the humidity in the blast. The furnace burden is added from the upper part of the blast furnace. In the process of smelting, only

half of the water enters the high-temperature zone and is decomposed, and with the increase of the temperature, the rest will turn into steam and enter the coal gas. The blast and fuel injection both enter from the blast furnace tuyere area, and all of the water is decomposed as a result of the high temperature of the raceway.

The free water carried by the furnace burden includes two parts: coke and raw material. The heat consumption of evaporation mainly refers to the heat needed for heating the furnace burden from normal temperature to $100^\circ C$ and for evaporating water into steam, and the associated heat consumption is relatively low. The algorithm is shown in formula 24.

$$Q_{H_2O} = Q_{H_2O-decomposition} + Q_{vaporation} \quad (24)$$

In the formula, $Q_{H_2O-decomposition}$ is the heat consumption of water decomposition and $Q_{vaporation}$ is the evaporation heat consumption of the free water in the furnace.

2.2.2.5 Heat taken away by molten iron, slag and top gas

The temperature is higher when the molten iron and slag are out of the blast furnace, and they will also take away some heat. The heat taken away by the top gas is affected by three parts: water vapor, dry gas and furnace dust. The algorithm is shown in formula 25.

$$Q_{dz} = Q_{molten\ iron} + Q_{slag} + Q_{top\ gas} \quad (25)$$

In the formula, $Q_{molten\ iron}$ is the heat taken away by the molten iron, Q_{slag} is the heat taken away by the slag and $Q_{top\ gas}$ is the heat taken away by the top gas.

2.2.2.6 Heat loss

It is inevitable that the heat loss of the blast furnace is higher, including the heat taken away by cooling water circulation, radiated into the surrounding space, etc. The algorithm is shown in formula 26.

$$Q_{loss} = Q_{income} - Q_{expenditure} \quad (26)$$

2.3 Theoretical combustion temperature of the tuyere

The formula for calculating the theoretical combustion temperature of the tuyere T_f is as follows:

$$T_f = \frac{Q_C + Q_{wind} - Q_{H_2O-decomposition} - Q_{gasification}}{C_{co} V_{co}^{hearth} + C_{H_2} V_{H_2}^{hearth} + C_{N_2} V_{N_2}^{hearth}} \quad (27)$$

In the formula, $Q_{\text{gasification}}$ is the heat consumption during the gasification of carbon, and its unit is $\text{kJ} \cdot \text{t}^{-1}$. C_{CO} , C_{H_2} and C_{N_2} are the specific heat capacities of CO, H₂ and N₂ at their theoretical combustion temperatures, respectively. $V_{\text{CO}}^{\text{hearth}}$, $V_{\text{H}_2}^{\text{hearth}}$ and $V_{\text{N}_2}^{\text{hearth}}$ are the gas volumes of CO, H₂ and N₂ in the hearth region, respectively, and their unit is $\text{m}^3 \cdot \text{t}^{-1}$.

2.4 Establishment of the mathematical model

Based on the material balance and heat balance of the blast furnace, the mathematical model of a gas-injection blast furnace is established. The concrete model is shown in Figure 2.

Figure 2: Mathematical model of a gas-injection blast furnace

The relative error in the material balance should be controlled to within 0.3%, and the heat loss in the heat balance should be controlled at approximately 5%, which can meet the operation requirements of the blast furnace. If the error values exceed this range, the production parameters need to be modified and recalculated.

3 Study of the change regulations of the parameters

The raw material used in the process of gas injection is the field data of a 2500 m³ blast furnace at Handan Iron and Steel Company based on 200 kg pulverized coal, in which gas serving as the alternative to pulverized coal is injected into the blast furnace. Using the material balance and heat balance calculations, the changes of the blast furnace af-

Table 1: Main parameters of the blast furnace

Parameters	Numerical value
Coal ratio / (kg/tHM)	0
Direct reduction	0.1
Hydrogen utilization ratio / %	0.4
Blast humidity / %	1.5
Top gas temperature / °C	200
Blast temperature / °C	1200
Gas composition	30% H ₂ and 70% CO

Figure 3: Relationships between the volume of the coal gas injected and the theoretical combustion temperature of the tuyere

ter the coal gas is injected are analyzed, and the parameters under different melting conditions are also compared. The parameters involved in the calculation are shown in Table 1.

3.1 Theoretical combustion temperature

The effects of the volume of coal gas injected and the oxygen enrichment rate on the theoretical combustion temperature are shown in Figure 3 and 4, respectively. It can be clearly seen from Figure 3, that when the oxygen enrichment rate is 10%, the theoretical combustion temperature decreases with the increase of the volume of coal gas injected, but it only slightly changes within the range of 2050 to 2100°C. This is because with the increase of coal gas injection, the gas volume of blast furnace hearth increases, which leads to the decrease of theoretical combustion temperature. As seen from Figure 4, when the volume of coal gas injected is 600 m³/tHM, the theoretical combustion temperature increases with the increase of the oxygen enrichment rate. Notably, the theoretical combustion tem-

Figure 4: Relationships between the oxygen enrichment rate and the theoretical combustion temperature of the tuyere

perature greatly changes within the range of 1950~2500°C as the oxygen enrichment rate increases from 5% to 30%. From the above analyses, it can be concluded that the volume of coal gas injected and oxygen-enriched rate have a synergistic effect, which can keep the theoretical combustion temperature within a reasonable range, but the effect of the oxygen enrichment rate on the theoretical combustion temperature is greater than that of the gas volume. Through the calculation of the theoretical combustion temperature and its comparison with the field blast furnace, it is revealed that when the oxygen enrichment rate is controlled at 10%, the target value of the theoretical combustion temperature of the tuyere can be controlled between 1950 ~ 2200°C, which can meet the requirements of blast furnace smelting.

3.2 The oxygen enrichment rate and the volume of coal gas injected

After the blast furnace oxygen enrichment and coal gas injection, the reduction degree of the shaft is not only an important factor in determining the fuel consumption of the blast furnace but is also a significant parameter defining the coke rate, gas-injection volume, oxygen consumption, volume of the top gas and other indicators. Therefore, the direct reduction degree is an important parameter to study [14, 15]. The relationships of the gas-injection volume with the oxygen enrichment rate and direct reduction degree are presented in Figure 5. As seen from the figure, under the condition that oxygen enrichment rate is 10%, the direct reduction degree first slows and then decreases rapidly with an increasing volume of coal gas injected. The reason for this effect is that the quality of the gas in the bosh and shaft of the blast furnace is improved with the in-

Figure 5: Relationships between the gas-injection volume and the oxygen enrichment rate and direct reduction degree (Online version in color)

Figure 6: Relationships between the oxygen enrichment rate and the blast volume and volume of coal gas injected (Online version in color)

crease of the gas volume and oxygen enrichment rate, and as a result, the concentration of the reducing gas increases, which promotes the reduction of the shaft and contributes to the development of indirect reduction.

Under the conditions of oxygen enrichment and coal gas injection, the relationships of the oxygen enrichment rate with the blast volume and volume of coal gas injected are calculated using the mathematical model. The result is shown in Figure 6. As seen from the figure, when the volume of coal gas injected is constant, the blast volume for smelting the unit of pig iron decreases with an increase in the oxygen enrichment rate, but the degree of decrease gradually weakens as the oxygen enrichment rate becomes more than 10%. In addition, with an increase in the volume of coal gas injected, the oxygen enrichment rate increases to ensure a suitable theoretical combustion temperature in the tuyere.

The relationships of the gas-injection volume with the oxygen enrichment rate and coke rate are shown in Figure 7. As shown in the figure, when the oxygen enrichment

Figure 7: Relationships between the gas-injection volume and the oxygen enrichment rate and coke rate (Online version in color)

Figure 8: Effects of different coke rates on the composition of the blast furnace top gas (Online version in color)

rate is constant, the coke rate almost declines linearly with the increase of the volume of gas injected. However, when the volume of gas injected is more than 800 m³/tHM, the decreasing trend of the coke rate slows, which indicates that the combustion rate and the replacement ratio of the gas both decrease after the volume of gas injected becomes more than 800 m³/tHM. In addition, with the increase of the volume of coal gas injected, the oxygen enrichment rate needs to increase to adapt to the change of the theoretical combustion temperature in the tuyere.

3.3 Composition of the top gas

The effects of the coke ratio, gas-injection volume and oxygen enrichment rate on the composition of the blast furnace top gas are described in Figure 8 to Figure 10, respectively.

From Figure 8, it is easy to observe that under the condition that the oxygen enrichment rate is 10% and the volume of coal gas injected is 600 m³/tHM, the CO content increases while the contents of H₂ and CO₂ decrease with

Figure 9: Effects of the gas-injection volume on the composition of the blast furnace top gas (Online version in color)

Figure 10: Effects of the oxygen enrichment rate on the composition of the blast furnace top gas (Online version in color)

the increase of the coke rate. In addition, we can see from Figure 9 that when the coke rate is 200 kg and the oxygen enrichment rate is 10%, with an increase in the volume of coal gas injected, the contents of CO, H₂ and CO₂ in the top gas of the blast furnace increase, and notably, the content of the CO increases rapidly. The reason for this effect is that the utilization rate of the coal gas which replaces the coke in the reduction reaction decreases with the increase of the gas-injection volume, so the amount of CO in the top gas will increase more quickly.

From Figure 10, we can see that the oxygen enrichment rate increases with the increase of the volume of coal gas injected to maintain a suitable theoretical combustion temperature. When the coke rate is 200 kg and the volume of coal gas injected is 600 m³/tHM, the contents of CO and H₂ in the top gas increase to different extents. The content of CO in the top gas increases rapidly when the oxygen enrichment rate is higher than 10%. The reason for this phenomenon is that the utilization rate of the gas gradu-

ally increases with the increase of the gas-injection volume and the oxygen enrichment rate. In addition, the content of CO_2 in the top gas first increases and then decreases. The reason for this phenomenon is that the volume of coal gas injected increases with the increase of the oxygen enrichment rate. Notably, when the oxygen enrichment rate is relatively low, the effect of an increasing of oxygen enrichment rate on the volume of the top gas is less than that of the increase of the gas-injection volume. Therefore, the content of CO_2 in the top gas first increases and then decreases.

4 Study on the effect of H_2

In the new process of oxygen enrichment and coal gas injection, the proportion of H_2 in the injected gas is quite high, which is different from the case in the smelting of a traditional blast furnace. In thermodynamics, the ability of CO to reduce wustite is stronger than that of H_2 when the temperature is below 810°C , and H_2 is more effective than CO when the temperature is above 810°C . In addition, it is acknowledged that the diffusion coefficient of $\text{H}_2/\text{H}_2\text{O}$ is higher than that of CO/CO_2 by 3~5 times. Therefore, although the temperature is lower than 810°C , the reduction rate of H_2 is higher than that of CO .

Based on the study of the reducing ability of reductive gases, the reduction of iron oxides by H_2 and CO mixed gases and by CO alone is compared. The reduction rate of ore with mixed gas is 15% higher than that with CO gas alone. In addition, with an increase in the H_2 content of the mixed gas by 1%, the reduction rate increases by 3%~5%. The reason for this phenomenon is that the carburization of CO takes place after forming the initial iron layer, and as a result, the C will diffuse to the interface between the iron and wustite and produce gas. The gas will form a high pressure in the interior of the oxide and break the iron membrane to open the way for the H_2 that has a relatively strong reduction power. Therefore, these results indicate that the contribution of H_2 to reduction is obvious [16, 17].

The effect of the H_2 content on the top gas is shown in Figure 11. It can be seen from Figure 11 that the contents of CO and CO_2 in the top gas decrease as the proportion of H_2 is further increased. In addition, the direct reduction degree of iron gradually decreases with an increasing H_2 content of the coal gas injected, but it slows after the H_2 content becomes more than 30%. The reason for this effect is that the utilization rate of H_2 gradually decreases with the increase of the H_2 content. As seen from Figure 12, the theoretical combustion temperature rises with the increase of

Figure 11: Effect of the H_2 content in the gas on the top gas (Online version in color)

Figure 12: Effect of the H_2 content in the gas on the theoretical combustion temperature

the H_2 content in the gas. However, the H_2 content in the gas cannot undergo an unlimited increase because the volume of gas produced gradually decreases with an increasing H_2 content of the coal gas injected. As a result, the volume of reducing gas used for the reaction of iron oxides in the middle and upper parts of the blast furnace will be insufficient, and the heat for ore reduction will also be reduced. Therefore, the proper gas composition is very necessary to effectively control the amount of gas produced in the blast furnace and the theoretical combustion temperature of the tuyere.

Table 2: Qualities of various materials

Name	Mixed ore	limestone	Coke rate	Coal rate	slag	furnace dust
Number, kg/tHM	1565.30	3	368	150	310.64	10

Table 3: Chemical composition of the pig iron (%)

Si	Mn	P	S	C	Fe
0.42	0	0.101	0.031	4.3	94.65

Table 4: Chemical composition of the slag (%)

Name	CaO	MgO	SiO ₂	Al ₂ O ₃	FeO	S	CaO/SiO ₂
Component, %	38.22	10.59	34.86	14.86	0.41	1.1	1.04

Table 5: Composition analysis of the top gas (%)

CO ₂	CO	N ₂	H ₂	CH ₄	O ₂	ηCO
17.3	24.5	56.6	0.60	0.60	0.40	41.39

5 Comparison of smelting effect between new technology and the conventional process

5.1 Smelting effect

The blast furnace in Tangshan Iron and Steel Company is used as the comparison object. The qualities of different kinds of materials are listed in Table 2, the chemical compositions of the pig iron and slag are shown in Table 3 and Table 4, respectively, and the composition of the top gas is presented in Table 5.

The composition of the hot metal that includes Si, Mn, P, and S is determined, but the C content is calculated by the empirical formula.

$$[C] = 4.3 + 0.3 \times [Mn] - 0.27 \times [Si] - 0.32 \times [P] - 0.032 \times [S] = 4.3\%$$

$$[Fe] = 100 - [C] - [Si] - [Mn] - [P] - [S] = 94.65\%$$

The comparison of the smelting effect between the new process with oxygen enrichment and coal gas injection and the conventional blast furnace process at Tangshan Iron and Steel Company is shown in Table 6. From Table 6, we can infer some results.

1. The coke in the new process mainly plays the role of a skeleton to maintain the permeability of the stock column, and the required heating agent and reducing agent can be provided by the coal gas and other

sources. Compared with the traditional process, the new process can significantly reduce the coke ratio. According to the simulation calculations for the new process, the blast furnace coke ratio is determined to be 200 kg/tHM. At present, Baosteel No. 1 BF has achieved good results with a coal injection ratio of 260.6 kg/t and a coke ratio of 249.7 kg/t [18]. Furthermore, broad industrial testing of furnace top gas injection proves that the coke ratio of a blast furnace can be reduced by approximately 20% after adopting this process. Therefore, the coke ratio of 200 kg/tHM in the blast furnace can be realized theoretically.

2. During the new process of coal gas injection, the decomposition of CO₂ and H₂O in the lower part of the blast furnace is an endothermic reaction, which effectively solves the issue that the theoretical burning temperature of the blast furnace tuyere is too high. Moreover, the water equivalent of gas rises with the increase of H₂, and as a result, the heating of burden in the upper part of the blast furnace is improved, while the contradiction between the upper cooling and the lower heating of the blast furnace is solved. Compared with the traditional process, the theoretical combustion temperature of the new process can be adjusted flexibly by controlling the volume and components of the coal gas injected, which is a great advantage of the blast furnace with coal gas injection.

Table 6: Comparison of the smelting effect between the new process and the conventional blast furnace process

Project Name	Calculation results in GOBF of Tang Steel				Calculation results in blast furnace of Tang Steel			
Coke, kg/tHM	180	200	240	200	Coke rate, kg/tHM	374.9		
Coal rate, kg/tHM	0	0	0	0	Coal rate, kg/tHM	150		
coal gas	600	600	500	700	Jiao Ding, kg/tHM	17.23		
	541.07	541.07	450.89	631.25	Lump coal, kg/tHM	3.43		
Air volume	454.14	498.39	642.32	471.85	Fuel ratio, kg/tHM	545.56		
	590.38	647.90	835.02	613.40	Hot air, kg/tHM	1134.36		
Oxygen	88.47	97.09	125.13	91.92	oxygen	Volume, m ³	44.20	
	126.38	138.70	178.75	131.31	Weight, kg	63.14		
Furnace top coal gas	1209.72	1277.93	1360.96	1354.76	Furnace top coal gas	Volume, m ³	1760	
	1559.48	1641.46	1784.61	1690.84	Weight, kg	2385.58		
	28.27	29.44	25.52	34.97	CO, %	24.97		
	10.73	10.26	8.45	11.10	H ₂ , %	0.61		
	26.53	24.96	25.15	21.50	CO ₂ , %	17.36		
	28.69	29.81	36.32	26.44	N ₂ , %	56.16		
	5.78	5.53	4.55	5.98	H ₂ O, %	0.25		
Theoretical combustion temperature, °C	2181.99	2184.84	2076.71	2292.11	Theoretical combustion temperature, °C	2183		
Direct reduction degree of iron	0.1	0.1	0.1	0.1	Direct reduction degree of iron	0.45		
Hydrogen utilization rate, %	35.03	35.11	35.2	38.7	Hydrogen utilization rate, %	0.1		
Oxygen enrichment rate, %	15	15	10	20	Oxygen enrichment rate, %	3		
Gas volume in bosh, m ³ /t	1223.01	1283.72	1449.05	1270.9	Gas volume in bosh, m ³ /t	1444.65		
Heat loss, kJ · t ⁻¹	-1.07	2.34	4.42	2.46	—	—		

3. Through the simulation calculations for the heat balance in the new process, the oxygen enrichment rate is controlled at approximately 10%, the gas volume injected is approximately $600 \text{ m}^3/\text{tHM}$ from the blast furnace tuyere, which can be used as reducing agent to serve as an alternative to coke and pulverized coal. The volume of coal gas injected will rise with the increase of the oxygen enrichment rate, but it cannot increase indefinitely. In general, the theoretical combustion temperature will be too low if the volume of coal gas injected is more than $1000 \text{ m}^3/\text{tHM}$, and as a result, the normal physical and chemical reactions in the lower part of the blast furnace cannot be guaranteed. In fact, the hydrodynamic factors and the decrease of the output and the displacement ratio are both important restrictive links for the gas injection volume.
4. During the smelting conditions of the new process, the calculation results show that the volume of the reducing gas in the blast furnace greatly increases, and the reduction rate of the ore is not the restrictive link. Notably, the heating rate and the permeability of the burden become the major issues, and the preheating of the blast and the combustion of the gas will provide most of heat. With the increase of the ratios of CO and H_2 in the top gas, nitrogen, as a heat carrier, will be replaced by H_2 and CO in theory. Compared with the conventional smelting process, the direct reduction degree of the gas-injection process is greatly reduced. Therefore, the heat required for smelting a unit of pig iron is decreased.
5. Under certain conditions of the oxygen enrichment rate, the calculation based on the heat balance and thermodynamic data of the reaction between CO and H_2 reveals that the gas volume burned in the tuyere to serve as an alternative to 200 kg pulverized coal is $148 \text{ m}^3/\text{tHM}$, and the gas volumes that serve as alternatives to coke in the reduction reaction and in the combustion reaction are $281 \text{ m}^3/\text{tHM}$ and $100 \text{ m}^3/\text{tHM}$, respectively. Therefore, the total volume of coal gas injected is $529 \text{ m}^3/\text{tHM}$. In addition, it can be seen from the heat balance that the heat income from coke combustion in the tuyere decreases with the reduction of the coke rate, but it can be compensated by the physical heat of the coal gas injected and the oxidation heat of the reducing gas.

5.2 Relationship between the H_2 enrichment gas and the blast furnace operation

The theoretical and practical results show that the N_2 content of the blast in the blast furnace with oxygen enrichment and in the coal gas injected is low, and the volume of gas required for one ton of the unit pig iron decreases. As a result, the smelting strength is greatly improved [19]. It is proposed that when the coal gas is injected into the blast furnace, on one hand, using the reduction of the products of the gas combustion reaction can effectively decrease the theoretical combustion temperature, and on the other hand, the heat brought by the gas to the upper part of the blast furnace can meet the heat requirement of this location.

It can be seen from Figure 13 that the volume change of iron oxide is obviously different when it is reduced in different atmospheres. With the increase of the temperature, the iron oxide expands first and then shrinks in an H_2 environment. The maximum expansion is 180% at 1173K, but the iron oxide shrinks first and then expands in the environments of pure CO, 50% H_2 and 50% CO, and pure CH_4 , and it shrinks to the maximum at 1123K, which is -25%, -7% and -11%, respectively. Due to the different properties of H_2 and CO, iron oxides behave differently during the reduction process.

The major factor that affects the increase of the utilization coefficient of a blast furnace is the resistance loss caused by a large amount of gas passing through the burden. When the pressure drops, which is an effect produced by the passage of the gas through the burden, and reaches a certain value, the descent of the burden will be affected. As a result, the operating stability of the blast furnace will be destroyed. It is generally acknowledged that the pressure drop is mainly related to the porosity of the burden and the flow rate of the gas when the temperature distribution and top pressure are constant. The proportion of H_2 in the gas produced by the new process blast furnace is much higher than that in the ordinary blast furnace. With the increase of H_2 content in the gas, the reduction rate of the burden is increased [20]. Before entering the melting state, the iron oxide has been completely reduced. On the one hand, the content of FeO in the initial slag is low, the amount of liquid initial slag formed is reduced, and the permeability of the burden in the melting zone is improved; On the other hand, a large number of metal iron appears in the burden earlier, and the metal iron also has certain resistance to the deformation of the burden, which is also helpful to maintain the permeability of the charge layer [21]. In addition, the characteristics of H_2 include a high thermal conductivity, a small atomic radius, easy dif-

Figure 13: Volume changes of iron oxides reduced under different temperatures and atmospheres

fusion, etc., and the resistance loss caused by H_2 passing through burden layers with the same porosity is smaller than that caused by other gases. Studies found that the volume of iron oxides reduced by CO will expand, but the volume of iron oxides reduced by H_2 will shrink. Therefore, the permeability of the burden will be improved during the process of heating and reduction.

Therefore, with the increase of H_2 content, the penetration ability of gas is enhanced, the resistance loss of charge column is reduced, and the permeability of burden is obviously improved. In fact, the productivity of the modern blast furnace is mainly prevented from increasing by the flooding phenomenon in the bosh. However, the generation of the flooding phenomenon [22] will be effectively avoided after the coal gas is injected into the blast furnace.

6 Conclusion

1. When the volume of coal gas injected is constant, the blast volume needed for smelting a unit of pig iron gradually reduces with the increase of the oxygen enrichment rate. When the oxygen enrichment rate is greater than 10%, the decreasing trend of the blast volume slows.
2. Under the condition of an oxygen enrichment rate of 10%, the direct reduction degree greatly decreases, and the coke rate almost linearly decreases with an increasing volume of coal gas injected. When the volume of the gas, however, is greater than 800 m^3/tHM , the coke rate decreases slowly. With the increase of the gas-injection volume, the oxygen enrichment rate is increased to ensure the proper theoretical combustion temperature of the tuyere.
3. When the oxygen enrichment rate is controlled at approximately 10% and the volume of coal gas injected is 600 m^3/tHM , the CO content of the top gas in-

creases with the increase of the coke rate, while the H_2 and CO_2 contents both decrease. When the coke rate is 200 kg and the volume of coal gas injected is $600\text{ m}^3/\text{tHM}$, with the increase of the oxygen enrichment rate, the contents of CO and H_2 in the top gas increase, but the content of CO_2 increases first and then decreases. When the oxygen enrichment rate is 10%, the content of CO_2 is the highest.

4. With the increase of the H_2 content in the coal gas injected, the direct reduction degree of iron gradually decreases, the theoretical combustion temperature increases, and the volume shrinkage of the burden increases. During the heating and reduction process, the permeability of the burden will not be deteriorated, and gas injected into blast furnace can effectively avoid the flooding phenomenon.
5. When the volume of the gas injected is $600\text{ m}^3/\text{tHM}$ and the oxygen enrichment rate is controlled at approximately 10%, the theoretical combustion temperature of the tuyere can be controlled at $1950\sim 2200^\circ\text{C}$, which can serve as a reducing agent to provide alternatives to coke and pulverized coal. This greatly reduces the degree of direct reduction and realizes smooth operation of the blast furnace. In the new process, the coal gas injected into the blast furnace can avoid the theoretical combustion temperature of the blast furnace tuyere being too high and solve the contradiction between the upper cooling and lower heating of the blast furnace.

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