Research Article

Yana Qie*, Qing Lyu, Chenchen Lan, and Shuhui Zhang

Energy Conservation and CO₂ Abatement Potential of a Gas-injection Blast Furnace

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Abstract: The gas-injection blast furnace (BF) is a new iron-making technology with an injecting gas instead of traditional pulverized coal injection (PCI) and recycling of the BF top gas through a gasifier. In contrast to traditional all-coke and PCI BFs, the coke rate will depend mostly on the heat consumption in a gas-injection BF with abundant injected gas, which results in a large coke-saving potential. Based on energy conservation, carbon recycling, CO₂ abatement and fuel cost, the degree of direct reduction should be between 0.2 and 0.3. In addition, in terms of the effects of the gas injected and the rich oxygen rate in the tuyere region, the optimum injection parameters were obtained, which can reduce the coke rate to 273.36 kg/tHM, carbon recycling to 100.72 kg/tHM and abate carbon dioxide emissions by 94.00 Nm³/tHM. Theoretically, the minimum total carbon consumption value is 399.73 kg/tHM. These results illustrate the great potential for carbon recycling and coke saving in gas-injection BFs without increasing total carbon consumption.

Keywords: gas-injection BF, energy conservation potential, coke-saving potential, CO₂ abatement, carbon recycling

1 Introduction

The energy-intensive iron and steel industry is responsible for approximately 6.7% of the total CO₂ emissions globally according to the International Energy Agency [1]. The majority of these emissions (over 70%) are produced by ironmaking blast furnaces (BFs), which also consume the largest amount of energy in the entire industry [2]. A traditional BF strongly relies on coke, and the coke rate is responsible for a large part of the production cost. Most of the new trends in blast furnace technology have focused on developing a coke alternative, such as natural gas injection, pulverized coal, waste plastic, biomass, coke oven gas and other hydrocarbon injections [3–10]. However, the practical applicability of these materials strongly depends on the natural resource distribution [11]. In addition, the use of a top gas recycling BF (TGR-BF) has received more interest in recent decades to reach strict energy conservation targets and achieve low CO₂ emissions [11, 12]. Top gas recycling and oxygen enrichment in a blast furnace are the primary technologies studied by the ULCOS project [13]. Currently, a number of studies on top gas recycling-oxygen blast furnace (TGR-OBF) have been carried out, including analyses of flow and reducing gas combustion in the tuyeres, CO₂ emissions and energy consumption [14–16]. Nonetheless, CO₂ capture investments cannot be neglected [17] and add an additional cost of $56/tCO₂ [18]. In addition, too much CO in gas will reduce the gas utilization [19, 20]. Currently, pulverized coal injection (PCI) is still the main method used to reduce the coke rate [21]. The highest reported PCI amount is approximately 250 kg/tHM (ton hot metal), which is similar to the coke amount. However, the impact of coal chemical properties must also be taken because they may prevent its complete combustion within the raceway, affect the gas permeability in the shaft, and contaminate the dead man zone, leading to irregular operation of the furnace and decreasing its productivity [12, 22].

The gas-injection BF is a new ironmaking technology that injects gas into tuyeres and recycles the BF top gas through a gasifier, which can provide a new gas source and effectively translate the CO₂ in the BF top gas into CO with a lower cost. In contrast to traditional BF with PCI, gas-injection technology can simplify the ironmaking process and recycle the BF top gas, which can contribute to lower emissions and higher productivities. The technological process is as follows [23, 24]: The BF top gas is injected into the gasifier as the gasifying agent. → Coal gasification occurs in the gasifier. → H₂-rich gas is produced. → H₂-
rich gas is heated in the gas heating device. → The high-temperature gas and hot air are injected into the furnace through the tuyere. The technological process is shown in Figure 1.

Figure 1: A diagram describing the operation of the gas-injection BF.

2 Energy conservation and CO₂ abatement calculations for gas-injection BFs

2.1 Parameter collection

To predict the carbon consumption characteristics in a gas-injection BF, systems traditionally supplied by only coke (‘all-coke’) and a traditional BF with PCI were used as comparisons. The conditions for coke, pulverized coal, iron-bearing feed and hot metal are shown in Table 1, 2 and 3 based on the conditions used by Tangshan Iron and Steel Enterprises in China.

2.2 Carbon consumption calculation

Carbon consumption in the BF ironmaking process can be divided into five aspects [33], including carburization of molten iron (\(w(C)_{carburization}\)), reduction of microelements (\(w(C)_{Si,Mn,P}\)), direct and indirect reduction of iron oxides and energy consumption. The first three carbon consumption mechanisms [32] are the same in all three cases (traditional all-coke BF, traditional PCI BF and gas-injection BF), and the results are shown in Table 4.

For the reduction of ferric oxides, a series of reactions can occur at temperatures greater than 570°C, i.e., \(\text{Fe}_2\text{O}_3 \rightarrow \text{Fe}_3\text{O}_4 \rightarrow \text{FeO} \rightarrow \text{Fe} [32]\). When a large of gas moves away from the tuyere-raceway region and flow up in BF shaft, FeO reduction occurs at first, and then, \(\text{Fe}_3\text{O}_4\) and \(\text{Fe}_2\text{O}_3\) reduction occurs. The reduction of FeO and \(\text{Fe}_3\text{O}_4\) occurs as the gas in the BF increases, as follows [32]:

\[
\text{FeO}(s) + n\text{CO(g)} = \text{Fe(s)} + (n-1)\text{CO(g)} + \text{CO}_2(g) \quad (1)
\]

\[
\frac{1}{3}\text{Fe}_3\text{O}_4(s) + (n - 1)\text{CO(g)} + \text{CO}_2(g) = \text{FeO}(s) \quad (2)
\]

\[
+ (n - \frac{4}{3})\text{CO(g)} + \frac{4}{3}\text{CO}_2(g)
\]

The carbon consumption via indirect reduction (\(w(C)_i\)) can be obtained as follows.

\[
w(C)_i = n \times \frac{12}{56} (1 - r_d - r_{H_2}) \times w(\text{Fe}) + \frac{1}{3} \times \frac{12}{56} \times n 
\]

\[
\times \frac{3}{4} (r_d + r_{H_2}) \times w(\text{Fe})
\]
Although the gas utilization is different at various positions in a BF, the CO utilization reaches 45%-56% in the top gas during practical production, and this is expressed by Eq. (6). Meanwhile, the line of $w(C)_{CO} = 0.5$ means the carbon consumption when the CO utilization is 50% during the calculation [35],

$$\eta_{CO} = \frac{\phi_{CO}}{\phi_{CO} + \phi_{CO_2}} \times 100\% = \frac{w(C)_{CO_2}}{w(C)_{CO}} \times 100\% \quad (6)$$

Finally, from an energy consumption perspective, the carbon provided by fuels ($w(C)$) is presented as follows [36].

$$w(C) = w(C)_{combustion} + w(C)_{d} + w(C)_{SL,Mn,P} \quad (7)$$

$$w(C)_{combustion}(q_{CO} + q_{blast}) = \sum_{i} Q_{consumption,i} \quad (8)$$

$$Q_{reduction} = \sum_{i} Q_{reduction,i} = Q_{direct \text{ reduction}} \quad (9)$$

$$Q_{carbon \text{ reduction}} + Q_{SL,Mn,P \text{ reduction}} = \frac{152190}{56} w(Fe) \times r_d \quad (10)$$

$$+ \frac{11847}{12} \times 22.4 \times \frac{20883}{232} w(Fe) + \frac{8229}{12} \times \frac{11847}{12} \times \frac{20883}{232} \times \frac{8202}{22.4}$$

$$+ \frac{7974}{2} \times \frac{7044}{2} \times w(H_2) \times (1 - \eta_{H_2})$$

where $w(Fe)$ represents the mass of Fe per ton of hot metal, $n$ is the excess coefficient in the indirect reduction process of iron oxides (the minimum $n$ value is 2.33 [32] in traditional all-coke and PCI BF), $r_d$ and $r_{H2}$ indicate the degrees of direct reduction and hydrogen reduction, respectively, and $w(H_2)$ denotes the mass of $H_2$ in coal and the injected gas. Meanwhile, the H$_2$ utilization ($\eta_{H2}$) is assumed to be 40%, and the hydrogen reduction degree ($r_{H2}$) is calculated by Eq. (4).

$$r_{H2} = \frac{w(H_2) \times \eta_{H2} \times (1 - \eta_{H2})}{w(Fe) \times \eta_{H2}} \times \frac{1}{2} \quad (4)$$

In the gas-injection BF, the amount of the reducing gas is sufficient, and the effect of the excess coefficient on the carbon consumption is not considered in the indirect reduction. In addition, the carbon consumption of the indirect reduction ($w(C)_{I}$) is the same as that consumed to generate $CO_2$ ($w(C)_{CO_2}$), which is shown as Eq. (5) [34].

$$w(C)_{I} = \frac{12}{56} \times \frac{1}{2} \times \frac{w(Fe)}{w(Fe)} \quad (5)$$

Although the gas utilization differs at different positions in a BF, the CO utilization reaches 45%-56% in the top gas during practical production, and this is expressed by Eq. (6). Meanwhile, the line of $w(C)_{CO} = 0.5$ means the carbon consumption when the CO utilization is 50% during the calculation [35].
Table 4: Carbon consumption for each processing segment

| Items                                                                 | Carbon consumption/kg-(tHM)$^{-1}$ |
|----------------------------------------------------------------------|----------------------------------|
| Molten iron carburization                                           | $w(C)_{\text{carburization}} = 43.4$ |
| Reduction of minor elements                                          | $w(C)_{\text{Sl,Mn,P}} = 12/28*2^{*}[\text{Si}] + 12/55^{*}[\text{Mn}] + 60/62^{*}[\text{P}] = 5.83$ |
| Direct reduction                                                     | $w(C)_{\text{d}} = 12/56^{*}[\text{Fe}]^{*}r_{d} = 202.69 r_{d}$ |
| Indirect reduction in traditional all-coke and PCI BF                | $w(C)_{i} = 472.27-354.21 r_{d} -354.21 r_{\text{H}2} = 445.87-354.21 r_{d}$ |
| Indirect reduction in a gas-injection BF                             | $w(C)_{i3} = w(C)_{\text{CO}2} = 304.04-202.69 r_{d} -202.69 r_{\text{H}2} = 288.93-202.69 r_{d}$ |
| Carbon provided by coke in a traditional all-coke BF                 | $w(C)_{1} = 214.53+424.73 r_{d} +53.84 r_{\text{H}2} = 215.85+424.73 r_{d}$ |
| Carbon provided by coke in a traditional PCI BF                      | $w(C)_{2} = 93.12+424.73 r_{d} +53.84 r_{\text{H}2} = 97.14+424.73 r_{d}$ |
| Carbon provided by coke in a gas-injection BF                        | $w(C)_{3} = 152.84+424.73 r_{d} +53.84 r_{\text{H}2} = 156.86+424.73 r_{d}$ |
| Utilization of CO = 50%                                              | $w(C)_{\eta_{\text{CO}=0.5}} = 577.87-405.39 r_{d}$ |

\[ q_{\text{blast}} = \frac{1}{24} \times \frac{0.21}{0.79} + 0.21 + \left( \int_{298}^{T_{\text{blast}}} c_{P_{O_2}} dT \right) \]

where $w(C)_{\text{combustion}}$ (kg/tHM) represents the carbon burned in the tuyere-raceway region and is obtained after the second heat balance shown in Eq. (8) is solved [36]; $Q_{\text{consumption}}$ represents the heat consumption including the heat spent reducing oxides ($Q_{\text{reduction}}$) and the heat carried away by the top gas ($Q_{\text{topgas}}$), hot metal ($Q_{\text{hotmetal}}$), and slag ($Q_{\text{slag}}$). $Q_{\text{reduction}}$ (kJ/tHM) is calculated by Eq. (9). Ignoring the effect of volatiles in fuels on the top gas, $Q_{\text{topgas}}$ is obtained by Eq. (10). In addition, $Q_{\text{loss}}$ (kJ/tHM) is assumed to be 10% of the heat income. $V_{\text{blast}}$ (m$^3$/tHM) represents the volume of the hot blast and is calculated by Eq. (12). In addition, $c_{P_{O_2}}$ and $c_{P_{N_2}}$ represent the heat capacities of O$_2$ and N$_2$, respectively, and these values can be obtained from the literature [37]. Finally, $f$ is the rich oxygen rate and is assumed to be 2% in this paper.

In this paper, three scenarios, the traditional all-coke BF, traditional PCI BF and gas-injection BF, are compared on the basis of carbon provided by the coke, i.e., the energy provided by only coke ($w(C)_{1}$) in the traditional all-coke BF. When the injected gas conditions, such as the volume and gas composition, are the same as those of the gas produced by pulverized coal in the tuyere region, the essential difference between traditional PCI BF and gas-injection BF is due to the pulverized coal combustion. In terms of the heat consumption, the carbon provided by coke in the traditional PCI BF and gas-injection BF is $w(C)$, and $w(C)_{3}$, respectively, and can be calculated as follows.

\[ w(C)_2 = \frac{\sum Q_{\text{consumption}} - Q_{\text{coal}}}{Q_{\text{CO}} + q_{\text{blasts}}} + w(C)_{\text{d}} \]

\[ w(C)_3 = \frac{\sum Q_{\text{consumption}} - Q_{\text{gas}}}{Q_{\text{CO}} + q_{\text{blasts}}} + w(C)_{\text{d}} \]

\[ Q_{\text{coal}} = Q_{\text{combustion}} - Q_{\text{coal,blasts}} - Q_{\text{coal,decomposition}} \]

\[ = w(C)_{\text{coal,eta,burn}} - w(C)_{\text{Coal,eta,blasts}} - w(C)_{\text{Coal,eta,decomposion}} \]

\[ Q_{\text{gas}} = \sum_{i} n_{i}^{\text{injected}} \int_{298}^{T_{\text{gas, injected}}} c_{P_{i}} dT \]

where $Q_{\text{coal}}$ and $Q_{\text{gas}}$ denote the heat provided by the pulverized coal and injected gas and are calculated by Eq. (15) and Eq. (16), respectively. In addition, $w(C)_{\text{Coal}}$ signifies the mass of C in pulverized coal; $\eta_{\text{burn}}$ represents...
the burn rate of pulverized coal, which is assumed to be 90%; \( q_{\text{decomposition}} \) is the energy consumption during coal decomposition, which is assumed to be 836 kJ/kg; \( w(C)_{\text{coal}} \) is the mass of the pulverized coal, i.e., 167 kg/tHM; and \( n_{\text{injected}} \) represents the molar mass of the injected gas.

To predict the carbon consumption characteristics in a gas-injection BF and compare them with those of a traditional PCI BF, some gas-injection assumptions are made: (1) The gas volume injected is 700 m\(^3\)/tFe, which is equivalent to the gas volume produced by 167 kg of pulverized coal in a traditional PCI BF. (2) The temperature of the injected gas is 1200\(^\circ\)C, which is the same as that of the hot blast. (3) Using a different oxygen enrichment rate and coal amount, the ratio of CO and \( H_2 \) can be changed, but 33.78\%:10.07\% is used for the comparison with a traditional PCI BF. (4) The excess indirect reduction coefficient is 1 with a large amount of injected reducing gas. (5) The molten iron composition is consistent with that of traditional PCI BF, which is shown in Table 3. (6) The heat consumption items have the same valves as those in traditional PCI BF except for the reducing oxides. (7) \( H_2 \) participates only in the FeO reduction reaction in the high-temperature zone.

3 Results and Discussion

3.1 Analysis of the coke-saving potential of the gas-injection BF

The aforementioned equations and parameters established the relationship between the direct reduction degree \( r_d \) and the 5 carbon consumption aspects, and the results are shown in Table 4.

By adding \( w(C)_{\text{Sl,Mn,P}} \) and \( w(C)_{\text{carburization}} \) to \( w(C)_{d1}, w(C)_{l1} \) and \( w(C)_{\text{redox}} \), the relationship between the carbon consumption and \( r_d \) is obtained. The result id shown in Figure 2, which takes into account the chemical consumption and energy penalty.

As shown in Figure 2, the carbon consumption is clearly determined by chemical and heat consumption. For the traditional all-coke BF, the polylines OPQ indicate the carbon consumption with an increase in \( r_d \). The intersection point (P) shows that the carbon consumption is approximately 426 kg/tHM and the corresponding \( r_d \) is 0.495. When coke is replaced with pulverized coal as the reducing agent and energy source (PI section), the coke rate of the traditional PCI BF is 357 kg/tHM, which is consistent with the practical production rate, 355 kg/tHM. These results indicate that the calculation model is valid.

![Figure 2: Carbon consumption in different processes](image)

The coke for providing heat in the gas-injection BF \( w(C)_{j3} \) is lower than \( w(C)_{1} \) and higher than \( w(C)_{2} \) due to the lack of coal combustion heat in the tuyere region. When the gas utilization is 50%, the coke ratio of the gas-injection BF is 387 kg/tHM, which is higher than that of the traditional PCI BF. Although the carbon-conservation potential in the gas-injection BF is not exploited under these conditions, increasing the concentration of the injected reducing gases could result in a higher reduction potential with less coke (angular, striped area in Figure 2).

Figure 2 shows that the coke conservation potential of the gas-injection BF can be analyzed in 3 zones:

1. When \( r_d \geq b \), the BF carbon consumption is determined by the heat consumption, and the injected gas functions only as a physical heat carrier. However, injecting a large amount of CO decreases the CO utilization due to the lower calorific value of CO. In other words, the carbon-conservation potential in the gas-injection BF is not fully exploited when \( r_d > b \).
2. When \( a < r_d \leq b \), the BF carbon consumption is mainly decided by indirect reduction. The injected gas provides excess CO for the indirect reduction (AB section) and physical heat, which leads to a decrease in the coke rate from point A to point B.
3. When \( 0 \leq r_d \leq a \), the BF carbon consumption is mainly determined by indirect reduction. The injected gases provide excess CO and physical heat and are involved in part of the indirect reduction, which can significantly decrease coke consumption. Based on these analyses, the degree of direct reduction should be controlled for \( r_d < b \) and \( r_d \leq a \) to exploit the coke-saving potential of the gas-injection BF.
In summary, with abundant injected gas, the coke rate of the gas-injection BF is determined by the heat consumption (line GH), whereas, that of the traditional all-coke and PCI BFs is decided by the indirect reaction and heat consumption (polylines OPO), respectively. In addition, by ignoring the excess coefficient effect, the gas-injection BF carbon consumption is shown as the polylines FDH when more reducing gas is injected. The minimum carbon consumption and coke rate are located at points D and G, respectively. Therefore, the degree of direct reduction should not be more than the value of p in terms of the carbon-conservation and coke-saving potential.

### 3.2 Carbon recycling and CO₂ abatement calculations

The gas-injection BF process recycles the CO₂ in the BF top gas through a gasifier [32, 38–40], which can save carbon resources and efficiently reduce CO₂ emissions.

\[
C + 1/2O_2 = CO + 117,490kJ \tag{17}
\]

\[
C + CO_2 = 2CO - 165,800kJ \tag{18}
\]

In the gasifier, the transformation of \( CO_2 \rightarrow CO \) produces a direct energy consumption of 165,800 kJ/mol and decreases the energy income by 117,490 kJ/mol [34] because the gasification reaction consumes carbon, which can no longer combust. The summation of these two parts is the additional energy consumption required in the gasifier to transform one mole of CO₂, and this energy must be provided by additional carbon combustion. The carbon consumption in the gasifier is shown in Eq. (19), which is obtained from Eq. (17) and Eq. (18) in terms of the chemical energy conservation [34]. In addition, the total energy of the potential CO₂ abatement is calculated by Eq. (20).

\[
x(C + 1/2O_2) + C + CO_2 = 2CO + xCO + 117490kJ \tag{19}
\]

\[
\eta_{CO_2\text{ utilized}} = \frac{1}{2 + x} \times 100\% \tag{20}
\]

Meanwhile, the CO, which is present in an equimolar amount, in the BF top gas can also be recycled. Therefore, the carbon-conservation potential of the injected carbon is expressed as follows.

\[
\eta_{C\text{ recycling}} = \frac{1 + 1}{2 + x + 1} \times 100\% \tag{21}
\]

where \( \eta_{CO_2\text{ utilized}} \) and \( \eta_{C\text{ recycling}} \) represent the percentages of the reduced CO₂ emissions and carbon conserved from the carbon carried by the injected gas respectively, these values are 22.67% and 36.96% based on Eq. (20) and Eq. (21), respectively.

The carbon recycling (\( w(C)_{\text{recycling}} \)) and CO₂ emission reduction (\( w(C)_{\text{emission reduction}} \)) amounts can be calculated as follows.

\[
w(C)_{\text{recycling}} = w(C)_{\text{injected}} \times \eta_{C\text{ recycling}} \tag{22}
\]

\[
w(C)_{\text{CO₂ emissions reduction}} = w(C)_{\text{injected}} \times \eta_{CO_2\text{ utilized}} \tag{23}
\]

\[
w(C)_{\text{total}} = w(C)_{\eta CO=0.5} - w(C)_{\text{recycling}} \tag{24}
\]

For the gas-injection BF, the total carbon consumption (\( w(C)_{\text{total}} \)) is expressed as Eq. (24) when the CO utilization is 50% and the recycled carbon is excluded. The influence of \( r_d \) on the potentials of \( w(C)_{\text{recycling}} \), \( w(C)_{\text{CO₂ emissions reduction}} \) and \( w(C)_{\text{total}} \) is shown in Figure 3(a). In addition to the carbon consumption, the effect on fossil-fuel and process-related CO₂ emissions is analyzed for the cost calculation. The total fuel cost, i.e., the sum of the coke and coal costs, is obtained from Eq. (25). Thus, if the excess coefficient effect is ignored (n=1), then the fuel cost is calculated as Eq. (26).

\[
w(C)_{\text{total fuel cost}} = \left\{ \begin{array}{ll}
w(C)_{\text{total}} - w(C)_{\eta}\phi(C)_{\text{coal}} \times p_{\text{coal}} & r_d \leq b \tag{25} \\
w(C)_{\text{total}} - w(C)_{\gamma} \phi(C)_{\text{coker}} \times p_{\text{coker}} & r_d > b \end{array} \right.
\]

\[
w(C)_{\text{fuel cost}} = \left\{ \begin{array}{ll}
w(C)_{\text{total}} - w(C)_{\gamma} \phi(C)_{\text{coal}} \times p_{\text{coal}} & r_d \leq a \tag{26} \\
w(C)_{\text{total}} - w(C)_{\gamma} \phi(C)_{\text{coker}} \times p_{\text{coker}} & r_d > a \end{array} \right.
\]

where \( \psi(C)_{\text{coal}} \) and \( \psi(C)_{\text{coker}} \) denote the fixed carbon contents of coal and coke, 74.37% and 86.00%, respectively; and \( p_{\text{coal}} \) and \( p_{\text{coker}} \) represent the price of coal and coke, respectively. The compositions and prices of fuel are dynamic based on the market, region and species, especially for coal, which includes diverse species such as brown coal, bituminous coal, anthracite coal and others. Here, we adopt 2000 RMB/tcoke and 900 RMB/tcoal as moderate values from Tangshan Iron and Steel Enterprises in China for the fuel cost calculations, which includes additional transportation costs. Figure 3 (b) relates the fuel cost and carbon recycling amount to \( r_d \) to reflect the gas-injection BF conservation potentials of these aspects.

As shown in Figure 3 (a), the total carbon consumption, including the gasifier, is expressed by the polylines...
MNH and is substantially lower than that in a traditional BF (polylines OPQ). In addition, the hatch area represents the carbon recycling potential, and the upper portion is the CO$_2$ abatement potential. In addition, detailed information for $w(C)$ recycling is shown in Figure 3 (b). Although $w(C)_{\text{total}}$ reaches a minimum when $r_d = b$, $w(C)_{\text{recycling}}$ is 0, and the gas utilization is lower. Therefore, the direct reduction degree should be lower than $b$ to exploit the carbon conservation and CO$_2$ emission reduction potential. Ignoring the excess coefficient effect, the carbon consumption minimum should be located at point D based on the analysis in section 2.3.2. In addition, when $r_d = a$, $w(C)_{\text{total}}$ is lower than that in a traditional BF (426 kg/tHM), which shows that more than 85 kg/tHM of carbon can be recycled without increasing the total carbon consumption. In addition, even in the scenario $r_d \leq a$, the potential for fuel cost savings and carbon recycling can fully compensate for the increasing carbon consumption, as shown in Figure 3 (b). In addition, the total fuel cost is also lower than that in a traditional BF (860 RMB/tHM). Based on the energy conservation, carbon recycling, CO$_2$ emissions reduction and fuel cost, the direct reduction degree should be maintained in the zone of $r_d \leq a$, which is consistent with the previously presented findings.

3.3 Optimum operation parameters for energy conservation in a gas-injection BF

A number of operating parameters, such as the $r_{H_2}$, rich oxygen rate and gas volume, influence energy conservation. The hydrogen content in coal is much higher than that in coke. The energy consumption is affected by the hydrogen addition and volume of gas injected in the gas-injection BF, as shown in Figure 4 (a) and Figure 4 (b), respectively. Moreover, the rich oxygen rate is a significant factor in inner variable distributions in BFs, such as the temperature, gaseous composition and gaseous volume, and thus, this rate should also be considered in this calculation (Figure 4 (c)).

Figure 4 (a) shows that in contrast to other carbon consumption mechanisms, $w(C)_{\eta\text{CO}}=0$ and $w(C)_{\text{sharply decrease with increasing in } r_{H_2} \text{ (hydrogen addition)}, which reveals that the energy consumption will decrease with a H$_2$ addition in the gas-injection BF. In addition, the amount of released carbon oxides is also reduced by saving energy. As shown in Figure 4(b), compared with the other carbon consumption mechanisms, $w(C)_{\text{decreases with an increase in the injected gas volume. With same amount of } w(C)_{\text{burn}} \text{ in the tuyere region, the physical heat carried by a hot blast will reduce with higher rich oxygen rate, which results in more carbon being needed to provide energy (} w(C)_{\text{3}} \text{), as shown in Figure 4 (c). In addition, based on the results obtained from the thermodynamic calculations and kinetics experiments on ore reduction with H$_2$ and CO additions [41], the maximum reducing gas content should be 10% H$_2$+50% CO to ensure a higher gas utilization and reduction rate in the gas-injection BF. The relationship between the BF bosh gas conditions and lower part of the operation parameters was established based on the balance of carbon and oxygen [32]. To summarize the aforementioned investigation, a roadmap of the calculation model is shown as Figure 5.

With the same bosh gas volume and 10% H$_2$+50% CO in the belly as in a traditional PCI BF, the effect of the injected gas volume on the coke rate is shown in Figure 6, which fully considers the influence of the injected gas conditions (volume, composition and temperature) and the oxygen enrichment rate in the tuyere region.
As shown in Figure 6, with an increase in the injected gas volume, the coke rate first decreases before increasing and the rate achieves a minimum with 775 Nm$^3$/tHM of injected gas. To guarantee a sufficient heat and reasonable gas volume in the BF bosh, the rich oxygen rate should correspondingly increase, which will result in a higher coke rate with more than 775 Nm$^3$/tHM of injected gas. In addition, the optimum parameters of a lower operation schedule are shown in Table 5, and the specific energy conservation information is shown in Figure 7.
Table 5: Optimum parameters of a lower operation schedule in the gas-injection BF

| Temperature / Volume / Composition / Temperature / Volume / Rich oxygen | Injected gas conditions | Hot blast conditions | Rate / % |
|---|---|---|---|
| °C Nm³/tHM % °C Nm³/tHM | | | |
| 1200 775 65.63% CO + 20.08% H₂ | 1200 635.72 0.15 | | |

have greater energy-conservation and coke-saving potential, as shown in Figure 7(b). In contrast to increasing the coke, the total carbon consumption gradually decreases with the addition of $r_d$. For $r_d \leq a$, the minimum values of the coke rate and total carbon consumption are 174.37 kg/tHM and 399.73 kg/tHM, respectively, and these values are due to improving the gas utilization and adjusting the composition of the injected gas. In addition, one advanced and mature coal gasification process, a shell gasifier [42–46], can be used to meet the syngas requirements for BF injection, which ensures the energy conservation and CO₂ abatement performances of the gas-injection BF.

On the basis of the aforementioned discussion, the gas-injection BF clearly has greater coke-saving potential under the optimum operation parameters based on theoretical calculation. These results provide a direction for the reduction of BF carbon consumption in practice. In BF operations, operating parameters can be adjusted to approach the optimal state of the theoretical calculation.

4 Conclusions

1. Compared with traditional all-coke and PCI BFs, the gas-injection BF has greater coke-saving potential with adjustment of the injection parameters, although its energy consumption is higher than that of the traditional PCI BF under equivalent conditions. In addition, with abundant injected gas, the coke consumption in the gas-injection BF will be determined by the heat consumption instead of both the chemical and heat consumption.

2. Top gas recycling can provide 36.96% of the carbon in the injected gas in the gas-injection BF. Based on a comprehensive consideration of energy conservation, carbon recycling, CO₂ abatement and fuel cost, the degree of direct reduction should not be greater than $a$ (the value of $a$ is approximately 0.3).

3. Based on the calculation results, the proper injection parameters, such as 775 Nm³/tHM of injected gas, 635.72 Nm³/tHM of blast, 0.15% rich oxygen rate and a 1200°C injection temperature are ob-
tained. These parameters can reduce the coke rate to 273.36 kg/tHM and total carbon consumption to 406.88 kg/tHM and increase the carbon recycling to 100.72 kg/tHM and CO$_2$ abatement to 94.00 Nm$^3$/tHM. These results reflect the strong potential for carbon recycling and CO$_2$ abatement in the gas-injection BF.

4. The findings of theoretical calculation a direction for the reduction of BF carbon consumption in practice. In BF operations, operating parameters can be adjusted to approach the optimal state of the theoretical calculation.

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