Research Article

Computational Study of Hot Gas Injection (HGI) into an Ironmaking Blast Furnace (BF)

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Blast furnace (BF) ironmaking is the most important process that produces hot metal (HM) from iron-bearing materials continuously, rapidly, and efficiently. To date, the process is considered to have reached its limit in view of the achieved high process efficiency. In addition, the required high-quality materials are expensive and gradually getting depleted. Hot gas injection (HGI) into the shaft of the BF is an emerging technology recognized potential to solve the aforementioned problems. However, so far, limited information and studies are available, most of which are preliminary studies with regard to the feasibility and aerodynamics of the technology. This hindered the understanding and thus the effective use of this technology. This work presents a numerical study of the multiphase flow, heat, and mass transfer in a BF by a CFD-based process model. The effects of injection composition in terms of CO and CO₂ contents in HGI are studied first. The calculated results reveal that HGI of 100% CO delivers the best BF performance. Then, the effects of key variables in relation to HGI of 100% CO, including position, rate, and temperature, are systematically studied. The in-furnace states and overall performance parameters have been analysed in detail. The results show that, through appropriate control of the injection variables, it is possible to achieve improved BF performance including low fuel rate and high productivity, which are considerably affected by the HGI parameters. The BF process model is also demonstrated to be a cost-effective tool in optimizing the key variables of HGI in BF for obtaining optimum process efficiency.

1. Introduction

The blast furnace (BF) ironmaking process is the most important technology by which hot metal (HM) is continuously, rapidly, and efficiently reduced from iron-bearing materials [1]. The process heavily relies on the use of carbonaceous materials including coke and pulverised coal (PC) to generate the required energy, which makes up more than 70% of the energy consumption and production cost in an integrated steelwork. In addition, the necessitated coke is an expensive raw material and gradually getting depleted. Therefore, there is a considerable amount of social and economic concerns over the current BF ironmaking process.

However, it should be pointed out that, after 200 years of development, the process is recognized to have approached its limit in view of the achieved high process efficiency. Consequently, any considerable amount of fuel reduction only based on the optimization of the traditional BF is difficult to attempt [2, 3].

In recent decades, much attention has been given to the implementation of new technologies on the BF. The new technologies include the hot charge of burden materials [1, 4, 5], injection of novel matters, such as PC [6], oil [7], natural gas [8, 9], and hot gas [10–12], and use of new burden materials including highly reactive coke [13, 14] and carbon composite pellet [15]. These technologies have been

examined at various levels and proved to be useful for improving BF performance. Among these technologies, the hot gas injection (HGI) into the BF is considered useful due to its possible advantages [1, 16]. The hot gas can be generated from the combustion and reforming of cheaper fuel materials and off-gas within the steelwork, which is more flexible and economical than the combustion of coke and PC. It can be used to intensify the smelting of burden materials and reduce the fuel rate. Compared with fossil fuel injection, HGI avoids the decreased adiabatic flame temperature and the generation of unburnt powders. In addition, HGI can be flexibly implemented at the BF shaft, which avoids the flow of high-speed gas in the low permeability wet zone.

HGI was first introduced by Lance in the 1920s, in which it was used to partly replace the reducing gas generated from combustion of carbonaceous materials in the raceway [17]. After that, little progress was made until middle 1960s. Using an experimental BF (EBF) with a hearth diameter of 4.6 m, HGI of reformed gas at 1000°C was tested in Belgium [17]. In late 1970s, Fink employed this technology on an oxygen BF (OBF) to solve the thermal shortage problem [18]. After that, investigations have been intensively performed by various methods such as cold model [19], experimental scale [11, 20, 21], and commercial scale [10, 22] BFs as well as theoretical calculation [16, 18, 23–25], continuum models [10, 26–28], and discrete models [29, 30]. The EBF (inner volume 3.2 m³) [21] and numerical model studies [27] showed that HGI should contain less CO₂/H₂O due to the strong endothermic effect of carbon solution loss reaction and water gas reaction. The injection position is better to locate at the bottom of the thermal reserve zone in the BF shaft so that the reaction products (CO₂/H₂O) would not undergo severe solution loss [1, 21]. Besides, the temperature of injected gas should be at around 1000°C [1, 19] to maintain the temperature profile in the BF. A number of studies showed that HGI improves BF performance in view of decreased coke rate and increased productivity [21–23, 31]. It was also revealed that the penetration depth of injected gas is in proportion to the volume ratio of injected gas to gas generated from tuyere [1, 19, 29]. By using an EBF, it was shown that shallow penetration of HGI leads to less improved BF performance [11]. Recently, HGI is more frequently employed on the OBF as an enabling technology to address the thermal shortage phenomena in the upper furnace with several typical OBF processes established [18, 22, 24, 25, 32]. It is also considered as an essential part for realizing the zero-carbon footprint OBF process through injection of recycled top gas after CO₂ capture and storage. With those efforts, HGI has been considered promising and is currently adopted by two world-class projects aiming low carbon production, i.e., ULCOS in the European Union [17] and COURSE50 in Japan [11].

It is clear that the control of the operational parameters of HGI, including injection composition, position, temperature, and rate, has significant impact on the BF performance. However, thus far, a comprehensive study regarding the effects of key operational parameters of HGI on BF inner states and overall performance indicators is yet

available. This hinders the understanding and, therefore, the effective use of the technology. Considering that the iron-making BF is a complicated multiphase reactor accompanied with high temperature and hazardous conditions, instrumentation is difficult to access its inner states [33]. Also, it is difficult to use theoretical and experimental methods to conduct investigations comparable to a real BF situation. Alternatively, numerical models are playing an increasingly important role in investigating the BF ironmaking process, see, e.g., the reviews by different investigators [34–37]. Basically, the methods can be either discrete or continuum [38, 39]. Compared with the discrete models, the continuum models are considered more suitable for process modelling due to its computational efficiency. This work, for the first time, presents a comprehensive numerical study of the effects of HGI on BF performance, with respect to key performance indicators including injection composition, position, temperature, and rate. First, the BF process model used in this is briefly introduced. Then, the effects of HGI compositions in terms of varying CO and CO₂ content are performed. Based on the results, the optimum HGI composition is thus identified to improve BF performance. After that, a systematic study with respect to the key HGI variables including position, rate, and temperature using the identified optimum HGI composition is conducted. Detailed analysis with respect to the flow, heat, and mass transfer as well as thermochemical phenomena in the BF is carried out for optimizing the injection operational parameters.

2. Methods

The present mathematical model is a steady-state, axisymmetric multifluid model. It considers the region of a BF from the slag surface up to the burden surface. The phases considered including gas, solid, and liquid. Each phase in the model is described by separate conservation equations of mass, momentum, and enthalpy, with the key chemical reactions considered. Gas is described by the well-established volume-averaged, multiphase, Navier–Stokes equations [39]. Solids are assumed to be the continuous phase that can be modelled based on the typical viscous model used in multiphase flow modelling [39, 40], coupled with the method proposed by Zhang et al. [41] for determination of the deadman boundary. General convection-diffusion equations are applied to describe heat and mass transfer among the different phases. The model is in principle similar to other BF process models developed by different investigators [4, 40, 42–49], and moreover, it is able to model the layered burden structure in lumpy zone and cohesive zone (CZ) [40], as well as the varying stockline [40] as well as stock line variation [4]. The details of the model and relevant numerical techniques are available elsewhere [4, 40, 41, 46, 50, 51] and are not detailed in this paper for brevity. The governing equations, key chemical reactions, and transfer coefficients are summarized in Tables 1 and 2. In this work, the model is modified so that it is able to handle BF with HGI with varying injection composition, position, rate, and temperature within wide ranges.

TABLE 1: Governing equations of the present model.

Items		Description
Mass conservation		$\nabla \cdot (\varepsilon_i \rho_i \mathbf{u}_i) = S_i$, where $S_i = -\sum_k \beta_{i,k} R_k^*$
Momentum conservation	Gas	$\nabla \cdot (\varepsilon_g \rho_g \mathbf{u}_g \mathbf{u}_g) = \nabla \cdot \tau_g - \varepsilon_g \nabla p + \rho_g \varepsilon_g \mathbf{g} + \mathbf{F}_g^s$ $\tau_g = \varepsilon_g \mu_g [\nabla \mathbf{u}_g + (\nabla \mathbf{u}_g)^T] - (2/3) \varepsilon_g \mu_g (\nabla \cdot \mathbf{u}_g) \mathbf{I}$
	Solid	$\nabla \cdot (\varepsilon_s \rho_s \mathbf{u}_s \mathbf{u}_s) = \nabla \cdot \tau_s - \varepsilon_s \nabla p_s + \rho_s \varepsilon_s \mathbf{g}$ $\tau_s = \varepsilon_s \mu_s [\nabla \mathbf{u}_s + (\nabla \mathbf{u}_s)^T] - (2/3) \varepsilon_s \mu_s (\nabla \cdot \mathbf{u}_s) \mathbf{I}$
	Liquid	$u_l = 0; v_l = \text{constant}$
Heat and species conservation		$\nabla \cdot (\varepsilon_i \rho_i \mathbf{u}_i \varphi_{i,m}) - \nabla \cdot (\varepsilon_i \Gamma_i \nabla \varphi_{i,m}) = S_{\varphi_{i,m}}$ If $\varphi_{i,m}$ is $H_{i,m}$, $\Gamma_i = (k_i/c_{p,i})$ $S_{\varphi_{i,m}} = \delta_i h_{ij} \alpha (T_i - T_j) + \eta_i \sum_k R_k^* (-\Delta H_k)$ If $\varphi_{i,m}$ is $\omega_{i,m}$, $\Gamma_i = \rho_i D_i$, $S_{\varphi_{i,m}} = \sum_k \alpha_{i,m,k} R_k^*$ where $\varphi_{i,m} = \omega_{g,\text{CO}}, \omega_{g,\text{CO}_2}, \omega_{g,\text{H}_2}, \omega_{g,\text{H}_2\text{O}}, \omega_{g,\text{N}_2}, \omega_{s,\text{Fe}_2\text{O}_3}, \omega_{s,\text{Fe}_3\text{O}_4}, \omega_{s,\text{FeO}}, \omega_{s,\text{flux}}$
Phase volume fraction		$\sum_i \varepsilon_i = 1$
State equation		$p = \sum_i (y_i M_i) RT_g / V_g$

The model used in this work is well-developed and has already been validated at different levels. Firstly, it is able to predict the variations of in-furnace states and performance indicators with variation of key operational parameters such as coke rate and blast rate, which were qualitatively comparable with the practical observations of the BF process [4]. Also, the model is demonstrated to be able to well predict the measured results of experimental-scale BF [11, 43], including key performance indicators such as top gas temperature, top gas utilization factor, and productivity, as well as the in-furnace states with regards to layered CZ structure, gas temperature, and reduction degree. Also, it can precisely describe the overall performance indicators (top gas utilization factor, top gas temperature, and productivity) as well as the key in-furnace state (the position of CZ) in an experimental-scale OBF in China under the conditions both with and without injection of reformed coke oven gas [42]. These results confirm the general applicability of the model over a wide range of operations. For this sake, the model is not further validated and mainly focuses on its application in this work.

3. Simulation Conditions

Figure 1 shows the computational domain and an enlarged area demonstrating the representative computational cells. A commercial-scale BF with the inner volume of 5000 m³ is used as the target in this work. Assuming the symmetrical distribution of process variables, only half the BF is considered in the simulation for computational efficiency. The whole computational domain is divided into 527 × 129 nonuniform control volumes under the Cartesian coordinates, which ensures that the mesh is fine enough to precisely capture the complicated multiphase flow in different layers in the lumpy zone and CZ. The refining of the mesh shows that this mesh size gives mesh-independent numerical solutions. Based on a number of numerical trials, the computational parameters have been carefully selected so that results can get convergence within reasonable time and does not suffer from the problem of divergence. The relaxation factor of the velocity field is set at 0.5 and that of pressure is set at 0.2. The CFD residual is set to be 0.001. The total iteration number is set at

15000 for the give BF conditions considering the complexity of the BF ironmaking process.

The operational conditions for the BF operated without HGI (base case) is listed in Table 3. Burden materials including iron ore, coke, and flux are charged from the furnace top with the ore batch weight of 140 tonnes. A centre-developed radial burden distribution of the ore-to-coke ratio similar to that used by previous researchers [40, 43] is adopted in this work. The hot blast is blown into the BF at the flowrate of 7300 m³/min and at the temperature of 1200°C. Pulverised coal injection (PCI) is implemented at the rate of 1.37 t/min. Corresponding to the blast conditions, the composition, temperature, and flowrate of the reducing gas generated from the raceway are determined based on the local mass and heat balance and used as the inlet conditions of the gas phase, which is also listed in Table 3. This condition is used throughout the simulations for BF both with and without HGI. Note that the water content in the hot blast is negligible under the present condition. Thus, the reducing gas leaving the raceway only consists of CO and N₂. In the first part of this study, HGI with varying CO and CO₂ is used. To facilitate the implementation of top gas recycling and considering the top gas utilization factor is usually around 50% in a well-operated BF [1, 3], the CO content in the HGI is gradually increased from 50% to 100% at every increment of 10% to examine the effects of HGI composition on BF performance. The injection temperature is 900°C, and the injection rate is 1200 m³/min. The injection position is set at 5.25 m above the tuyere centre level in the BF. The optimum HGI composition in terms of improving BF performance is then determined. Based on the optimum HGI composition, a parametric study with respect to the injection position, rate, and temperature is performed. Since gas flow in the bosh zone is a major factor limiting the BF productivity and causes unstable phenomena such as flooding [1, 54], HGI is only practiced in the BF dry zone (belly and shaft) with varying position. The injection position is ranging from 5.25 m to 20.25 m (from the level of tuyere centre) and set up at every increment of 3 m. The injection rate is increased from 0 m³/min to 3000 m³/min at every increment of 600 m³/min, and injection temperature is increased from 500°C to 1300°C at the increment of 100°C.

TABLE. 2: Chemical reactions and transport coefficients in the present model

Terms	Formulation
$Fe_2O_{3(s)} + CO_{(g)} = Fe_{(s)} + CO_{2(g)}$ [52]	$R_1^* = 12\tilde{\epsilon}_{ore}\epsilon_{ore}P(y_{CO} - y_{CO}^*)/(8.314T_s)/(d_{ore}^2/D_{gCO}^e[(1-f_0)^{-1/3} - 1] + d_{ore}[k_1(1+1/K_1)]^{-1}\}$
$FeO_{(l)} + C_{(s)} = Fe_{(l)} + CO_{(g)}$ [53]	$R_2^* = k_2(A_c/V_b)\alpha_{FeO}, (A_c/V_b) = 0.468[\epsilon\phi_{coke}d_{coke}]$
$C_{(s)} + CO_{2(g)} = 2CO_{(g)}$ [52]	$R_3^* = (6\tilde{\epsilon}_{coke}\epsilon_{coke}Py_{co_2}/(8.314T_s)/d_{coke}/k_f + 6/(\rho_{coke}E_fk_3))$
$FeO_{(s)} \longrightarrow FeO_{(l)}$ [46] $Flux_{(s)} \longrightarrow Slag_{(l)}$	$R_4^* = \langle T_i - T_{min,sm}/T_{max,sm} - T_{min,sm} \rangle_0 (\phi \omega_{sm} \rho_i \epsilon_i dA/M_{sm} Vol_{cell})$
$Fe_2O_{3(s)} + H_{2(g)} = Fe_{(s)} + H_2O_{(g)}$ [52]	$R_5^* = (\pi \cdot d_{ore}^2 \phi_{ore}^{-1} N_{ore} \cdot 273 \cdot P(y_{H_2} - y_{H_2}^*)/(22.4T_{solid}))/\{1/k_{f5} + (d_{ore}/2)[(1-f_s)^{-1/3} - 1]D_{s5} + [(1-f_s)^{2/3}k_5(1+1/K_5)]^{-1}\}$
$C_{(s)} + H_2O_{(g)} = CO_{(g)} + H_{2(g)}$ [52]	$R_6^* = (\pi d_{coke}^2 \phi_{coke}^{-1} N_{coke} \cdot 273 \cdot Py_{H_2O}/22.4T_{solid})/(1/k_{f6} + 6/d_{coke}\rho_{coke}E_fk_6)$
$CO_{(g)} + H_2O_{(g)} = CO_{2(g)} + H_{2(g)}$ [53]	$R_7^* = 7.29 \times 10^{11} (y_{CO})^{1/2} (y_{H_2O}) (P/T_{gas})^{3/2} \epsilon (\exp(-67300/RT_{gas})/\sqrt{1+14.158y_{H_2}PT_{gas}}) - 1.386 \times 10^{10} (y_{CO})^{1/2} (y_{H_2})^{3/2} \epsilon (\exp(-57000/RT_{gas})/\sqrt{1+4.24y_{CO}PT_{gas}})$ $R_8^* = k_8 (A_v/V_B) C_{SiO_2}$ $k_8 = 7.59 \times 10^4 \exp(-62870/RT_s)$
$SiO_2(l) + 2C = Si + 2CO(g)$	
$SiO_2(l) + 2C(l) = Si(l) + 2CO(g)$ [53]	
Diffusion	Gas [53]
Conductivity	Gas [53] Solid [53] Liquid [46]
Heat transfer coefficients	$Nu = 2.0 + 0.6(Pr)^{0.333} (Re_g)^{0.5}$ $h_{gs} = 0.3h_{gs}^e$ and $h_{gs}^e = Nu k_g / d_s$ $h_{g-slab} = (0.203Re_g^{0.33} Pr^{0.33} + 0.220Re_g^{0.5} Pr^{0.4}) k_g / d_s$ $E_{gl} = 4.18 \times 10^{-4} \epsilon_g \rho_g \mu_g C_{pg} (\epsilon_g \rho_l \mu_l)^{0.35} Re_{gl}^{-0.37} \cdot (Sc_g/Pr_g)^{0.667} (T_l - T_g)$ $h_{sl} = 1/(1/h_s + 1/h_l), h_s = 2\sqrt{k_s C_{ps} \rho_s \tilde{u}_l - \tilde{u}_s /\pi d_s}$ $h_l = (k_l/d_s) = 2\sqrt{Re_{sl} Pr_l} / (1.55\sqrt{Pr_l} + 3.09\sqrt{0.372 - 0.15Pr_l})$ where $Re_{sl} = \varphi_d \rho_s \tilde{u}_l - \tilde{u}_s /\mu_l$ and $Pr_l = C_{pl}\mu_l/k_l$

FIGURE 1: Schematic illustration of the computational domain (a), and its representative grid arrangement (b).

TABLE 3: Inlet conditions in the base case simulated.

Variables	Values
Gas:	
Inlet velocity (m/s)	188
Inlet gas component (mole percentage)	38.925 pct CO; 0.0 pct CO ₂ ; 0.0 pct H ₂ ; 0.0Pct H ₂ O; 61.075 pct N ₂
Inlet gas temperature (°C)	2070.6
Top pressure (atm)	2.0
Solid:	
Ore t·HM	1.64
Ore components (mass fraction)	Fe ₂ O ₃ 0.6566; FeO 0.1576; CaO 0.0652; MgO 0.0243; SiO ₂ 0.06; Al ₂ O ₃ 0.0295; MnO 0.0061; P ₂ O ₅ 0.008
Average ore particle size (m)	0.018
Coke (kg/t·HM)	300
Coke components (mass fraction)	C 0.857; Ash 0.128; S 0.005; H 0.005, N 0.005
Average coke particle size (m)	0.045
Flux (t/t·HM)	0.0264
Flux components (mass fraction)	CaO 0.438; MgO 0.079; SiO ₂ 0.024; Al ₂ O ₃ 0.033; CO ₂ in CaO 0.344; CO ₂ in MgO 0.082
Ore voidage	$0.403(100d_{ore})^{0.14}$
Coke voidage	$0.153\log d_{coke} + 0.742$
Average ore/(ore + coke) volume ratio	0.5923
Burden temperature (°C)	25

Note that the position and profile of CZ in a BF is of major importance in affecting the BF performance and stability [4, 40], which also largely determines the lower furnace state. With the same CZ, a BF operated under different conditions could lead to similar flow and thermal conditions at the lower part of the furnace, producing HM with similar qualities [7]. Since the implementation of HGI on a BF is a novel technology that could introduce much uncertainty, the positions of CZ in BF with various HGI

operations are kept similar to those in the BF operation without HGI, to secure a comparable and stable production. This is achieved by gradually adjusting the coke rate at BF top via a “trial and error” method. In this work, the BF operation without HGI is considered to be in stable operation and is treated as the base case. As an example, Figures 2(a) and 2(b), respectively, show the porosity distributions and enlarged CZ profiles in the BF without HGI and with HGI of 100% CO both before and after coke

FIGURE 2: Simulated porosity distribution (a) and CZ (b) for the BF operated without HGI (I), HGI of 100% CO before coke reduction (II), and after coke reduction (III).

reduction. It is shown that inverse V-shaped CZs are obtained in all the operations, which is mainly controlled by the burden distribution pattern and hence porosity distribution [55, 56]. However, the CZ position rises significantly due to the HGI of 100% CO. This suggests that there is excessive energy in the BF with HGI of 100% CO before coke reduction. As seen from Figure 2(b), with proper adjustment of coke rate, similar CZ profiles and positions can indeed be obtained for the operations with and without HGI. The achieved fuel rate and productivity are calculated and shown in Figure 3 in Section 4.1. Such a method is adopted throughout this work when quantifying the coke rate for a given operation with HGI.

4. Results and Discussion

4.1. Effects of HGI Composition. The effects of varying HGI composition are examined first by changing the CO and CO₂ contents. shows the heating-up process in the BF without HGI and with HGI of different compositions. To be clear, only the results for BF without HGI, with HGI of 50% CO + 50% CO₂ and HGI of 100% CO are shown. In addition to the in-furnace solid temperature for the BF without HGI and with different HGI being represented by flooding, the lines representing the solid temperature for the base operation (BF operated without HGI) are also added to all the cases considered for comparison. As seen from the figure, for all the operations, the solid temperature is higher in the centre region and gradually decreases to the peripheral

region, as affected by the centre developed burden distribution. Hence, the temperature profile in the furnace is not significantly affected by HGI but still dominated by the burden distribution patterns [55, 56]. Compared with the BF without HGI, the solid temperature is higher in the upper furnace with HGI regardless of the injection composition, which suggests that heat energy is supplied to the upper furnace and HGI operations result in more severe cooling losses of heat from the wall [57]. The simulation result is in line with the previous study [23] based on an EBF with injection of hot reformed gas. It is also found that the solid temperature is the highest for BF with HGI of 50% CO + 50% CO₂, which should be attributed to the decreased productivity and leading to a smaller thermal flow ratio in the upper furnace [1, 9, 21, 42].

shows the reduction degree together with the indirect reduction rate of iron ore in the BF without HGI and with HGI of different compositions. As seen from the figure, the reduction process is improved over the whole cross-sectional area for HGI of 50% CO + 50% CO₂ and injection of 100% CO in the furnace top part. This is corresponding to the increased upper furnace temperature that facilitates the indirect reduction rate of iron ore. It can also be seen from the figure that, eventually, all the operations can successfully finish the smelting process of iron ore at similar longitudinal levels. These are similar results as that observed on an EBF in LKAB [11], in which reformed coke oven gas was injected into the lower shaft. The EBF study showed that the

FIGURE 3: Calculated productivity (P), (a) PCI rate (PCR), (b) and coke rate (CR) (c) for the BF operated with different CO contents in HGI.

reduction process is mainly accelerated above the lower injection level and gradually approaches that in the base operation below the injection level. It can be seen from the figure that the composition of injected gas has strong impact on the chemical reactions in the furnace, especially the region near the injection inlet. The indirect reduction of iron ore is intensified in the operation with HGI of 100% CO. Interestingly, it was also noted that indirect reduction of iron ore was significantly delayed around the injection level and a “hollow” is formed in the operation of BF with HGI of 50% CO + 50% CO₂. It is because the local gas composition has already reached the reaction equilibrium and prevents the indirect reduction from further proceeding, while it is the opposite situation for the use of pure CO that has an effect on lowering down the local CO₂-to-CO ratio. The results for BF with HGI of CO are in line with the simulation [31] and EBF [1, 11] results, in which indirect reduction is intensified in the region near the injection inlet. However, it is seen that the region affected by HGI is small. This is due to the insufficient penetration, and therefore, the injected gas mainly flows in the peripheral region, which is in line with the

previous studies using EBF [11], cold model [10, 19], and numerical model [20, 42].

The coke rate consumed in a BF primarily consists of two parts, including those consumed through chemical reactions (direct reduction of iron ore and carbon solution loss reaction) and those combusted in front of tuyere to supply part of the required heat for the smelting process apart from the energy supplied by fuel materials' injection and external heat energy [1, 4]. Figures 6(a) to 6(c), respectively, plot the coke rate consumed through direct reduction (CR_{DR}), carbon solution loss (CR_{SL}), and combustion in front of tuyere (CR_{TY}) against the CO content in HGI. As seen from the figure, the coke rate consumed through direct reduction decreases when the CO content in HGI is increased. This should mainly be attributed to the intensified indirect reduction of iron ore in the region around the injection level, as stated above. Consequently, less iron ore is reduced through direct reduction by coke. It is also seen that only the BF with HGI of 50% CO + 50% CO₂ leads to increased coke rate consumed by direct reduction, compared with the base operation without HGI. This is because the iron ore in the peripheral region goes through the “hollow” region where indirect reduction of iron ore is significantly deteriorated. The coke rate consumed through carbon solution loss also decreases as CO content in HGI is increased. This is expected because the reducing gas atmosphere in the furnace is strengthened as more CO is injected into the BF, which inhibits the solution loss reaction. Figure 6(c) shows that the coke rate consumed through combustion in front of tuyere decreases when the CO content in the injected gas is increased. This is mainly because that the coke-consuming reactions, i.e., direct reduction and carbon solution loss, that are strongly endothermic are restricted, while indirect reduction that is mildly exothermic is intensified when CO content in the HGI is increased [1]. Thus, the heat requirement in the furnace becomes smaller, and less heat is required to be generated from the combustion of carbonaceous materials in the tuyere region.

The variations of the key performance parameters including productivity (P), PCI rate (PCR) and coke rate (CR) with CO content in HGI are calculated by the BF process model and shown in Figures 3(a) to 3(c) respectively. As seen from Figure 3(a), with the increased CO content in HGI, the productivity is increased. This is because the hot blast rate and hence the heat input for a unit time is kept constant for different operations considered in this work. As stated above, the heat required (as indicated by carbonaceous materials consumed through combustion in front of tuyere) for producing unit HM decreases, which means that more iron ore can be smelted into HM and the productivity increases accordingly. This is in line with a number of previous studies based on EBF [11, 23] and mathematical model [31]. As shown in Figure 3(b), in accordance with the change of productivity, since the PC is injected as a constant in unit time, the PCI rate (unit HM basis) is decreased when CO content in HGI is increased. As discussed above, since the coke rate consumed through direct reduction, carbon solution loss, and combustion in front of tuyere all

FIGURE 4: Simulated solid temperature distribution for the BF operated without HGI, HGI of 50% CO + 50% CO₂, and HGI of 100% CO.

decreases with the increased CO content in the HGI, the coke rate decreases consequently. This corresponds to the previous studies by various methods such as EBF [11, 23], mathematical model [31], and theoretical model [10], showing that HGI of reducing gas leads to decreased fuel rate. Note that compared with the base operation, all the BFs with injections show reduced coke rates except that with HGI of 50% CO + 50% CO₂, which indicates that the HGI with composition similar to the utilization factor of the top gas of a traditional BF deteriorates the BF performance.

The simulated results show that the HGI of 100% CO presents the best BF performance in view of the significantly increased productivity and decreased coke and PC rate. This is in accordance with the fact that a considerable amount of real BFs are operated with HGI of high CO contents [18, 22, 25, 58].

4.2. Parametric Study of HGI of 100% CO into BF. Based on the above results and considering that HGI of 100% CO can improve the BF performance, a systematic study with regard to the effects of HGI of 100% CO into BF is presented in the following section. The key HGI parameters considered include injection position, temperature, and rate. The effects of these parameters on the in-furnace states and performance parameters have been simulated and analysed.

To be succinct and convenience, only representative results are shown for each parameter considered, as the effects of changing these parameters on in-furnace states and performance indicators are monotonous. Note that the operation with the HGI injection rate of 0 m³ is the base operation. Figures 7(a) to 7(c), respectively, show the distributions of solid temperature in BFs operated with HGI of different positions, rates, and temperatures. As seen from the figure, despite of the changing parameters, the solid temperature gradually decreases from the centre region to the peripheral region, which is dominated by the burden distribution in the furnace. This is in line with the previous studies [55, 56]. The figures show that the upper furnace temperature is increased for BF with HGI of CO regardless of the HGI position, rate, and temperature. The temperature differences between BF with HGI and BF without HGI mainly exist in the region around and above the injection inlet. The temperature differences between BF with and without HGI are larger when the injection level is higher, especially in the BF top. This is because shorter distance is provided between the injected hot gas and burden materials when the injection level is higher, leading to more intensified heat transfer in the region above the injection level. Also, the increased injection gas rate leads to higher upper furnace temperature. This is easily understood as a higher injection rate leads to larger in-furnace gas flow rate, therefore

FIGURE 5: Simulated indirect reduction of iron ore and reduction degree for the BF operated without HGI, HGI of 50% CO + 50% CO₂, and HGI of 100% CO.

strengthening the convective heat transfer in the furnace. An increased HGI rate decreases the local temperature near the injection inlet as the HGI temperature is lower than the local burden temperature. Similarly, a decreased HGI temperature is seen to slightly decrease the local temperature in front of the injection inlet within very small region. Generally, the effects of varying HGI parameters on the temperature profile are small. This should be attributed to the fact that the injected gas mainly flows in the peripheral region within a narrow region, which goes through serious heat loss from the wall [23].

Figures 8(a) to 8(c), respectively, show the distributions of the reduction degree of iron ore together with the indirect reduction rate of iron ore in BFs operated with different injection positions, rates, and temperatures. As seen from the figure, compared with the BF operation without HGI, the reduction degree is increased in BF with HGI regardless of injection position, rate, and temperature since the reducing gas atmosphere in the furnace is strengthened. The improved indirect reduction of iron ore mainly exists in the region near and above the injection level. The reduction degree of iron ore in the BF shaft is more promoted when the injection

position is lower as a longer contacting time is provided between injected hot gas and burden materials. Similarly, the increased injection gas rate also improves the indirect reduction in the shaft as the CO concentration in the upper furnace is increased. Also, it was found that a lower injection gas temperature promotes the reduction of iron ore. This is easily understood as the temperature at the injection position is too high that restricts the indirect reduction of iron ore that is an exothermically reaction. Therefore, using HGI at lower temperature helps to alleviate the restriction of indirect reduction. However, it should be pointed out that such effect is small as the temperature profile is not much affected by HGI temperature.

The coke rate consumed through direct reduction, carbon solution loss, and combustion in front of tuyere with CO injection at different positions, rates, and temperatures are quantified and shown in Figures 9(a) to 9(c), respectively. As seen from Figure 9(a), compared with BF operation without HGI, the coke rate consumed through direct reduction is all reduced when HGI is adopted. It also shows that the amount of the reduced coke rate is larger when the injection position is lower, injection rate is larger, and

FIGURE 6: Calculated coke rates consumed through direct reduction (CR_{DR}), (a) and solution loss (CR_{SL}), (b) and combusted in front of tuyere (CR_{TY}), (c) for the BF operated with different CO contents in HGI.

injection temperature is lower. Such results are expected because a lower injection level provides a longer contacting distance between injected gas and burden materials. A larger injection rate intensifies the reducing gas atmosphere in the furnace. These both facilitate the indirect reduction in the shaft and inhibit the direct reduction and are in line with theoretical analysis [1]. In the contrary, an increased injection temperature promotes the direct reduction and suppresses the indirect reduction, as the direct reduction being strongly endothermic and the indirect reduction being mildly exothermic [1, 53]. As seen from Figure 9(b), lower injection position, larger injection rate, and lower injection temperature lead to decreased amounts of coke consumed by the solution loss reaction. This is because the solution loss reaction that being strongly endothermic is more developed in the lower furnace zone where the local temperature is high. As the injection level becomes lower, CO is injected to the region where solution loss is stronger and has more pronounced impact on suppressing the reaction. Also, the

region for HGI to flow in-furnace becomes larger and inhibits the solution loss reaction to a broader extent. An increased HGI rate of CO decreases the concentration of the reactant (CO_2) and increases the concentration of the product (CO), which is unfavourable for the reaction thermodynamically [1, 53]. Conversely, the increased temperature of HGI facilitates the solution loss reaction in the local area. However, the effects are limited since the influenced area is small. Figure 9(c) shows the variations of the coke rate combusted in the tuyere zone with different variables of HGI. As seen from the figure, the amount of the coke rate combusted in the tuyere zone decreases as the injection position becomes lower, injection rate becomes higher, and injection temperature becomes lower. These results are generally in accordance with the variation rates of coke consumed through direct reduction and solution loss, which are strongly endothermic. Interestingly, it was noticed that when the injection position moves down to a certain level, the reacted coke rate does not change much, while the

FIGURE 7: Simulated distributions of solid temperature for BF with HGI of CO at different positions (a), rates (b), and temperatures (c).

coke rate combusted in the tuyere region still decreases. The decreased coke rate combusted in the tuyere region should mainly be attributed to the improved heat transfer between HGI and burden materials as the contact distance becomes longer. Also it was noted that although HGI with higher temperature brings in more heat energy, the coke rate combusted in the tuyere region still increases. This means that the heat required by the direct reduction and solution loss outweighs that provided by the physical heat of HGI. Additionally, the heat energy brought by HGI suffers from

serious heat loss, and little can be transferred to the burden materials.

The effects of key HGI parameters including injection position, temperature, and rate on major performance indicators encompassing productivity, PC rate, and coke rate are calculated and shown in Figures 10(a) to 10(c), respectively. As seen from the figure, the productivity of the BF increases when the injection position is lower, injection rate is larger, and injection temperature is lower, which is in accordance with the decreased heat

FIGURE 8: Simulated distributions of the reduction degree for BF with HGI of CO at different positions (a), rates (b), and temperatures (c).

requirement by chemical reactions in the furnace (as reflected by the carbon consumed through strong endothermic reactions including direct reduction and carbon solution loss reflected in Figure 9) under the condition that the heat input in unit times from raceway is kept constant. Corresponding to changes of productivity, since PC is injected as a constant in unit time, the PCI rate (unit HM basis) increases as the injection position becomes higher, injection rate becomes smaller, and injection temperature becomes higher. It can also be seen from Figure 10(c) that the coke rate is lower when the injection position is lower, injection rate is larger, and injection

temperature is lower, as a result of the summed coke rate consumed through direct reduction, carbon solution loss, and combustion in front of tuyere. Generally, HGI with lower injection position, larger injection rate, and lower injection temperature is seen to better improve the BF performance in terms of increasing the productivity and decreasing the fuel rate.

4.3. Discussion. The BF ironmaking process is concerned about the utilization of CO in HGI and its efficiency of replacing the carbonaceous fuel materials (coke and PC). To

FIGURE 9: Calculated coke rate consumed through direct reduction (CR_{DR}) (a), solution loss (CR_{SL}) (b), and combustion in front of tuyere (CR_{TY}) (c), for BF with HGI of CO at different positions, rates, and temperatures.

be comparable, in this study, a term named “replacement ratio” is used to assess the efficiency of the varying key HGI parameters on replacing the carbonaceous fuel materials by CO in HGI. It is defined as the ratio of the molar amount of carbon saved from the reduction of coke and PC to the molar amount of CO used in HGI. The effects of injection position, rate, and temperature on the replacement ratio have been calculated and are shown in Figure 11. As seen from the figure, a lower injection position leads to a higher replacement ratio. Such a result is expected as an elongated contacting distance gives longer reduction and heating-up time between iron ore and injected gas. It can also be seen from Figure 11 that optimum values of the injection rate and temperature are found, respectively, at around 1200 m³/min

FIGURE 10: Calculated productivity (P) (a), PCI rate (PCR) (b), and coke rate (CR) (c), for BF with HGI of CO at different positions, rates, and temperatures.

and 900°C. It is explained here. When the injection rate is low and insufficient reactant (CO) and heat energy is provided to the local area, the kinetics of chemical reactions, mainly indirect reduction of iron ore, would not be significantly improved. When the injection rate is too high, the local iron ore is quickly reduced to a large extent and a large portion of the injected gas would not be effectively utilised and goes out of the BF. When injection temperature is low, the decreased local temperature suppresses indirect reduction in kinetics. In the contrary, when injection temperature is too high, the indirect reduction that being exothermic is thermodynamically restricted, which also leads to lower replacement ratio. These are similar results to the previous theoretical analysis [1] and modelling results [42]. Generally, it is noted that the replacement ratio, and thus, the

FIGURE 11: Calculated replacement ratio for BFs with HGI of CO at different positions, rates, and temperatures.

utilization efficiency of HGI is mostly affected by the injection position compared to the other parameters.

5. Conclusions

A well-developed and validated BF process model is modified to study the effects of hot gas injection (HGI) of varying parameters on BF inner states and performance indicators. The effects of injected gas composition are clarified first. And, this is followed by a systematic study of the effects of the key injection variable in relation to HGI with the optimum composition, with the following findings obtained:

- (1) Under the current operational, materials, and geometrical conditions, higher CO content in HGI leads to better BF performance in view of increased productivity and decreased fuel rate. HGI of 100% CO presents the best BF performance. Compared with the base operation without HGI, the BF performance is worsened when the CO₂ concentration in HGI exceeds 50%, in which a "hollow" region is formed where the indirect reduction of iron ore is significantly delayed.
- (2) Lower injection position, larger injection rate, and lower injection temperature are found to be favourable conditions for HGI to be employed on the BF, resulting in decreased fuel rates and increased productivities. These are achieved mainly through improved thermochemical behaviours in the BF.
- (3) Under the current simulation conditions, optimum injection rate and temperature in term of the best

utilization of CO in HGI can be found. The optimum value was established under the kinetics and thermodynamics restrictions. The injection position is found to have the largest impact on the utilization efficiency of CO in HGI.

It should be pointed out that the above conclusions are obtained under the specific conditions considered. The flows and thermochemical states of a commercial-scale BF are extremely complicated, affected by many variables related to the inner profile of furnace as well as operational and raw material conditions. This study mainly demonstrated the possible potential of implementing the HGI technology to improving the BF performance. Only the effects of the key variable including injection composition, position, rate, and temperature over a wide range are investigated. In the next step, it is necessary to conduct systematic studies to understand the effects of other pertinent variables and their interplays, to further achieve the optimum design and control of BF with HGI referring to different requirements on productivity and energy consumption.

Data Availability

The DAT data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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