Numerical investigation of the limit of coke rate reduction in an ironmaking blast furnace (BF)

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Abstract—Blast furnace (BF) ironmaking maintains its role as the predominating process for producing hot metal (HM) from iron ore. The process is highly carbon- consumption and emission intensive. Considering its massive production scale, any improvement of the process in terms of the operational parameters could result in significant social, environmental and economical benefits. The most concerned operational parameters of the BF is the coke rate, with the reduction of the coke rate being long time pursued. However, the limit of coke rate reduction for an operating BF is rarely attempted for safety and stability. Therefore, the limit for coke rate reduction for an operating BF largely remains implicit, with the underlying mechanism being unknown. In this work, a previously developed multifluid BF process model is used to investigate the limit of coke reduction on an experimental scale BF. With the gradual reduction of the coke rate, the BF is analysed in detail in terms of in-furnace multiphase flow, thermochemical behaviors as well as overall performance indicators. The minimum coke rate to maintain a targeted production is identified with the underlying mechanism for the BF operated with a coke rate at its limit explained. Also, possible measures for increasing the limits of coke reduction are proposed. This is done by increasing the hot blast temperature, which proves to be useful based on the simulation results. The results generated from this work should be useful to improve the BF ironmaking process efficiency, hence cutting CO₂ emission and guiding green production in the future.

1. Introduction

Blast furnace (BF) ironmaking is the dominating process that rapidly and efficiently reduces iron-bearing materials [1] to produce hot metal (HM), which accounts for more than 90 percent of the HM production worldwide [2]. However, the process is highly carbon- emission and consumption intensive. Within an integrated steelwork, it accounts for about 90% of the CO₂ emission [3, 4] and 70% of the energy consumption through the combustion of carbonaceous materials [5]. Therefore, there is a considerable amount of social and environmental concern over it. Considering its massive production...
scale (e.g., over 10000 tons per day for a 5000 m$^3$ BF), any improvement of this process, even being small, can result in significant social, environmental and economical benefits.

In practice, the most important parameter to measure the process efficiency of the BF is the fuel rate [1], which usually consists of coke rate and pulverized coal (PC) rate as injection of PC is increasingly practiced nowadays. In the past, many efforts have been made, aiming to reduce the fuel rate, particularly the coke rate considering it is expensive and getting depleted. These include the control of burden distribution [6-8], preparation of burden materials [9], high hot blast temperature [10] and optimization of BF inner profile [11]. With these efforts, the coke rate is seen to be decreased continuously. However, to date, a method to determine the limit for the coke rate of an operating BF is yet available with the underlying mechanism being unknown. This is because that ironmaking BFs are complicated reactors involving multiphase flows of gas, solid, and liquid with simultaneous heat and mass transfer as well as chemical reactions under harsh conditions of high temperature and pressurized operation [12]. As such, it is difficult to continuously perform fuel rate reduction on an actually running BF due to the safety and economical issues as well as the consideration of stable production.

Instead, computer modelling can overcome the above problem. It has been widely used to study the multiphase flows and thermochemical behaviors inside BFs (see the reviews by different investigators [12-16]). The numerical approaches applied to BFs can be discrete- or continuum- in terms of the treatment of solid phase [17]. Discrete-based simulations are theoretically more rational, especially for complicated particulate systems in BF. However, the discrete models are computationally too demanding to consider the whole number of particles in a BF, even the BF is on an experimental scale. In contrast, the continuum approach is better developed for modelling the in-furnace states and global performance of various scaled BFs, and thus considered more suitable for process modelling and applied research [12, 16].

In this work, a previously developed continuum-based BF process model is adopted to investigate the limit for coke rate reduction on an operating BF. This is done by gradually decreasing the coke rate and achieve the lowest level for retaining a normal production. Then, analysis is made based on the flow and thermochemical phenomena in-furnace as well as overall performance indicators under different conditions. In addition, high blast temperature is proposed as a possible measure to increase the limit for coke rate reduction and proved to be useful. Such results should be useful to guide the green production of BF in the future.

2. Methods

2.1 Model description
The present mathematical model is a steady-state, axisymmetric multi-fluid one. It considers the region of a BF from the slag surface in the hearth up to the burden surface in the throat. The phases considered including gas, solid and liquid. Each of them consists of one or more components, and each component has its own composition and physical properties. Each phase is described by the separate conservation equations of mass, momentum and enthalpy, with the simultaneous consideration of key chemical reactions. The model is in principle similar to other BF process models developed by different investigators [11, 18-26], combined with the techniques of modelling the layered burden structures in the lumpy zone and cohesive zone (CZ) [20] as well as stock line variation [18]. The details of the model and relevant numerical techniques are available elsewhere [18, 20, 23, 27-29] and are not detailed in this paper for brevity. The governing equations for the model are summarized in Table 1.

2.2 Model validation
The model has already been validated at various levels, which is briefly summarized below. Firstly, the model demonstrated the capability to predict the variations of in-furnace states and performance indicators with coke rate and blast rate, which were qualitatively compared with the general observations of BFs, showing consistent results [18]. Secondly, the previous study demonstrated that the model can reasonably predict the measurements of an experimental scale BF [11, 30], 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, the gas temperature at different height levels and reduction degree of iron ore. 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 oxygen BF in China under the conditions both with and without injection of hydrogen-intensive gas [19]. These confirms the applicability of the model over a wide range of operations. For this sake, the model is not further validated in this work, which mainly focuses on the model application.

Table 1 Governing equations of the present model.

| Items                          | Description                                                                 |
|-------------------------------|-----------------------------------------------------------------------------|
| Mass conservation             | \( \nabla \cdot (\varepsilon, \rho \mathbf{u}_i) = S_i \), where \( S_i = -\sum_k \beta_{i,k} R_k^* \) |
| Gas                           | \( \nabla \cdot (\varepsilon, \rho \mathbf{u}_i \mathbf{u}_i) = \nabla \cdot \tau - \varepsilon \nabla p + \rho \varepsilon \mathbf{g} + F^s_i \) |
| \( \tau = \varepsilon \mu \eta [\nabla \mathbf{u}_i + (\nabla \mathbf{u}_i)^T] - \frac{2}{3} \varepsilon \mu \eta (\nabla \cdot \mathbf{u}_i) \mathbf{I} \) |
| Momentum conservation        | Solid                                                                       |
| \( \nabla \cdot (\varepsilon, \rho \mathbf{u}_i \mathbf{u}_i) = \nabla \cdot \tau - \varepsilon \nabla p + \rho \varepsilon \mathbf{g} \) |
| \( \tau = \varepsilon \mu \eta [\nabla \mathbf{u}_i + (\nabla \mathbf{u}_i)^T] - \frac{2}{3} \varepsilon \mu \eta (\nabla \cdot \mathbf{u}_i) \mathbf{I} \) |
| Liquid                        | \( u_i = 0, \ v_i = \text{cons tan} t \)                                  |
| Heat and species conservation | \( \nabla \cdot (\varepsilon, \rho \mathbf{u}_i \phi_{i,m}) - \nabla \cdot (\varepsilon, \Gamma_i \nabla \phi_{i,m}) = S_{\phi_{i,m}} \) |
| if \( \phi_{i,m} \) is \( H_{i,m} \), \( \Gamma_i = \frac{k_i}{c_{p,i}} \) |
| \( S_{\phi_{i,m}} = \delta_i h_i \alpha (T_i - T_j) + \eta_i \sum_k R_k^* (-\Delta H_k) \) |
| If \( \phi_{i,m} \) is \( \omega_{i,m} \), \( \Gamma_i = \rho_i D_i \), \( S_{\omega_{i,m}} = \sum_k \alpha_{i,m,k} R_k^* \) |
| \( \phi_{i,m} = \theta_{g,CO}, \theta_{g,CO_2}, \theta_{g,H_2}, \theta_{g,H_2O}, \theta_{g,N_2}, \theta_{g,FeO}, \theta_{g,Fe}, \theta_{g,Co}, \theta_{g,Co_2} \) |
| \( \theta_{g,FeO}, \theta_{g,Fe}, \theta_{g,Co}, \theta_{g,Co_2}, \theta_{g,N_2} \) |
| where \( \delta_i h_i \) |
| Phase volume fraction         | \( \sum e_i = 1 \)                                                            |
| State equation                | \( p = \sum_j (\gamma_j M_j)RT_j / \nu_j \)                                |
3. Simulation conditions
For convenience, an experimental scale BF used in the previous experimental [30] and numerical [11] studies is adopted in this work. The experimental BF has an inner volume of 9 m$^3$. The throat diameter at the stock surface level and hearth diameter are 1.0 m and 1.4 m respectively. For computational efficiency, 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 380x50 non-uniform control volumes under the Cartesian coordinates, which ensures that the mesh is fine enough to precisely capture the complicated multiphase flow and thermochemical behaviors in the BF. The refining of the mesh shows that such mesh size presents mesh-independent numerical solutions. The operational conditions for the experimental are same to those used in the stage 1 operation in the experiment [30]. The coke rate for the base operation is 450 kg/t·HM and the corresponding productivity is 4.5 t·HM/m$^3$·day. For brevity, other information is not further detailed here.

Note that the finished product of the BF ironmaking process is the HM. The certain temperature of the HM is required to guarantee a smooth and stable production and this could vary from case to case according to the specific requirement. In this work, the least required HM temperature is set to be 20 °C higher than the melting temperature (1400 °C) of the HM. As so, the coke rate is gradually decreased until the least required HM temperature is reached while the other operational, materials conditions are kept unchanged.

4. Results and Discussion

4.1 Effects of reducing coke rate on BF inner states and performance indicators
The position of CZ is of key importance to the BF performance and production [1]. Fig. 1(a) shows the variation of CZ with the decrease of coke rate for the experimental BF. As seen from the figure, the position of CZ gradually shifts downwards with the decrease of the coke rate. This is easily understood because less fuel materials are combusted in the raceway to provide the thermal energy for processing the iron-bearing materials. The result is consistent with those observed through practical operation [1] as well as simulation [18]. Also, it is found that a minimum coke rate is required to maintain a smooth production of the BF, which is 15 kg/t·HM less than the base condition. As seen from Fig. 1(b), below this coke rate, the lumpy zone comes too close to the deadman and the dripping zone almost disappears, which suggests that the iron ore cannot be processed to HM at the least required temperature. Thus, a normal production cannot be secured.
Coke rate=450kg/t·HM  445kg/t·HM  440kg/t·HM  435kg/t·HM

Fig. 1 Schematic illustrations of (a) CZ and (b) porosity distributions with the change of coke rate.

Figs. 2(a) and (b) respectively shows the distributions of solid temperature and reduction degree for the BF operated at different coke rates. Clearly, the heating-up and reduction of burden materials are more promoted in the centre region and gradually becomes slower towards the peripheral region. This is corresponding to the burden distribution pattern and hence gas flow distribution that is more developed in the central region [22]. It can also be seen from the figures that the heating-up and reduction process of burden materials is delayed as the coke rate is decreased. This should be attributed to the increased thermal flow ratio caused by increased productivity as the coke rate is increased. Such results are in line with previous studies [1, 18]. Notably, it is also seen from Fig. 2(b), all the operations with different coke rates can successfully finish the reduction of iron ore. Such results suggest that even with the least required coke rate, the BF can secure a normal production.
Coke rate=450kg/t·HM  445kg/t·HM  440kg/t·HM  435kg/t·HM

Fig. 2 Schematic illustration of (a) solid temperature and (b) reduction degree in BFs with different coke rates.

Figs. 3(a) and (b) respectively shows the gas and solid flow in-furnace for the BF operated with different coke rates. It is seen from Fig. 3(a) that centre developed gas flow distributions are presented for the BF at different coke rates, which is mainly dominated by the burden distribution pattern specified at the furnace top [22]. As can be seen in Fig. 3(b), although the coke rate is decreased, the solid flow rate is generally larger. This is because the productivity and solid charging rate is increased. Also, it is found that a typical “plug flow” is observed for BFs operated at different coke rates. This is in line with the previous simulation results [12].
Coke rate=450kg/t·HM  445kg/t·HM  440kg/t·HM  435kg/t·HM

Fig. 3 Schematic illustration of (a) gas flow and (b) solid flow (b) in BFs with different coke rates.

The key performance indicators including productivity, HM temperature and fuel rate for BFs operated with different coke rates are calculated and shown in Figs. 4(a) to (c) respectively. It is seen from Fig. 4(a) that productivity generally increases with the decreased fuel rate. This is because as the coke rate is decreased, less coke rate is combusted in front of the raceway. Since the hot blast rate and PC injection are kept constant, the productivity is needed to be increased to meet the local mass balance. This is consistent with the results obtained through practical operation [1] and simulation [18]. As seen from Fig. 4(b), generally, the total fuel rate decreases with the decreased coke rate. This is due to that the PC rate for unit HM becomes smaller when the coke rate is smaller and productivity is larger, as the PC injection rate is kept constant in unit time. It is seen from Fig. 4(c) that the HM temperature at the slag surface gradually decreases with the decreased coke. Such a result is easily understood since a decreased coke (fuel) rate results in less fuel materials combusted in the raceway and less thermal energy were provided into the furnace. Thus, the burden materials are processed to a lower temperature level.

Fig. 4 Calculated key performance indicators including (a) productivity, (b) fuel rate and (c) HM temperature.
4.2 Effects of increasing hot blast temperature on the limit of coke rate reduction

The above results show that the limit of coke rate reduction for the BF is reached mainly because the limit for HM temperature is reached due to the decreased fuel rate combusted in the raceway and hence less thermal energy was provided. To lift the limit for coke rate reduction, the increase of hot blast temperature (from 1050 °C to 1150 °C) is adopted to supply excess thermal energy generated from the raceway.

Figs 5(a) to (d) respectively show the limit of coke rate for BFs operated with hot blast temperature at 1050 °C (base operation) and 1150 °C (modified case), as well as the corresponding key performance indicators including coke rate, fuel rate, HM temperature, and productivity. It is seen from Fig. 5(a) that the limit of coke rate for the BF operated at 1150 °C is about 10 kg/t·HM less than that in the base operation. Fig. 5(b) shows that compared with the base operation, the total fuel rate decreased by 15.7 kg/t·HM. However, as seen from Fig. 5(c), although the fuel rate is decreased when the hot blast temperature is higher, the HM temperatures for the BF operated with hot blast temperatures at 1050 °C and 1150 °C are almost the same, which is controlled at around 1700 K as that targeted in this work. Corresponding to the change of fuel rate when the hot blast temperature is increased, the productivity is increased. The mechanisms have been explained in the above section and are not detailed here for brevity. Fig. 5(d) shows that productivity for the BF operated at 1150 °C is around 0.22 t·HM/m³·day higher than that in the base operation. This is mainly because less energy is required from the combustion of carbonaceous materials at the raceway due to the supply of extra thermal energy by the hot blast. Such results are in line with the previous studies [1].

To understand the underlying mechanism of the above results, Figs. 6(a) and (b) are schematic illustrations of the CZ and porosity distributions in BFs operated at different hot blast temperatures at their coke rate limits respectively. It can be seen from Fig. 6(a) that the CZ position is lower for the BF operated at a higher hot blast temperature. It is also noticed that the CZ becomes thinner in the lower part as the hot blast temperature is higher while the single layer within the CZ remains the same thickness. This is because as the CZ approaches the tuyere region, the solid temperature gradient becomes larger. Thus, the temperature region for softening and melting becomes narrower and so is the layer for the CZ.
This is in line with the practical operation reported in previous literature [1]. As seen from Fig. 6(b), as the CZ position becomes lower when the hot blast temperature, the dripping zone area also becomes smaller. This means that less area is provided for the liquid HM to be heated up.

![Schematic illustration of (a) CZ and (b) porosity distributions in BFs with different hot blast temperatures.](image)

Fig. 6 Schematic illustration of (a) CZ and (b) porosity distributions in BFs with different hot blast temperatures.

Figs. 7(a) and (b) compare the reduction degree and solid temperature distributions in BFs operated at different hot blast temperatures at their coke rate limits. As can be seen from Fig. 7(a), compared with the normal hot blast temperature operation, the reduction of iron-bearing materials is slightly delayed at the operation with higher hot blast temperature. This is easily understood since the high hot blast temperature leads to increased productivity, which shortens the contacting time between the reducing gas and burden materials. Importantly, it is noticed that the reduction of iron-bearing materials can be successfully finished for both operations at different hot blast temperatures. It is interesting to note that in Fig. 7(b), compared with the base case, although solid temperature is lower in the upper furnace region but becomes higher in the lower furnace, particularly that near the raceway in the high hot blast temperature operation. The lower upper furnace temperature is attributed to the increased productivity, which shortens the contacting time and heat transfer time between the reducing gas and burden materials while the higher temperature in the raceway region is caused by the higher adiabatic flame temperature caused by higher hot blast temperature as shown in Fig. 7(c). The increased lower furnace temperature with the high hot blast temperature operation is important since it facilitates the heat transfer between gas-solid-liquid flow in the lower furnace, which guarantees the liquids flow can be processed to the targeted temperature.
Fig. 7 Schematic illustration of (a) reduction degree (b) solid temperature and (c) gas temperatures in BFs operated with different hot blast temperatures.

5. Conclusion
A CFD based multi-fluid BF process model has been extended and used to study the effects of coke rate and investigate the limit of coke rate reduction for an operating BF under specific conditions. A possible method to increase the limit of coke rate reduction has also been proposed and proved to be effective based on the simulated results. The following conclusions can be drawn from the present study:

1. As the coke rate of the BF is decreased, the productivity is increased while the hot metal temperature is decreased and the position of the CZ is lowered down. There exists a certain limit for reducing the coke rate, below which the hot metal temperature becomes lower than the target and the smelting of the iron-bearing materials cannot be finished;

2. The increase of hot blast temperature is useful to provide thermal energy to the lower furnace. It can achieve the same hot metal temperature as that in the base operation. It decreases the fuel rate and increases productivity.

3. Combined use of high hot blast temperature and low coke rate operation is potential to realize desired production as that in the normal operation. However, the thermal states in-furnace changed significantly as indicated by the higher gas-solid temperature in lower furnace (near raceway).

It should be pointed out that the results obtained in this work is under specific materials, operational and geometrical conditions give. For practical application, there is a need to consider more comprehensively regarding the operational, materials and geometrical conditions. The developed multifluid Bf process model can serve in this function as a cost-effective tool for better control, design and optimization of the BF ironmaking process.

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References
[1] Biswas, A.K., Principles of blast furnace ironmaking: theory and practice. 1981, Brisbane, Australia: Cootha Publishing House.
[2] Kurunov, I.F., The blast-furnace process - is there any alternative? Metallurgist, 2012. 56(3-4): p. 241-246.
[3] Orth, A., N. Anastasijevic, and H. Eichberger, Low CO2 emission technologies for iron and steelmaking as well as titania slag production. Miner Eng, 2007. 20(9): p. 854-861.
[4] Xu, C.B. and D.C. Cang, A brief overview of low CO2 emission technologies for iron and steel making. J Iron Steel Res Int, 2010. 17(3): p. 1-7.

[5] Babich, A.I., et al., Choice of technological regimes of a blast furnace operation with injection of hot reducing gases. Rev Metal Madrid, 2002. 38(4): p. 288-305.

[6] Park, J.I., et al., Development of the burden distribution and gas flow model in the blast furnace shaft. ISIJ Int., 2011. 51(10): p. 1617-1623.

[7] Liu, S., et al., Numerical Investigation of Burden Distribution in a Blast Furnace. Steel Res. Int., 2015. 86(6): p. 651-661.

[8] Li, Z.Y., et al., Numerical investigation of burden distribution in ironmaking blast furnace. Powder Technol, 2019. 353: p. 385-397.

[9] Natsui, T., et al., Evaluation of Sinter Reducibility and Coke Reactivity by Experimental Blast Furnace. Tetsu to Hagane, 2013. 99(4): p. 267-274.

[10] Nie, H.Q., et al., Numerical investigation of oxygen-enriched operations in blast furnace ironmaking. Fuel, 2021. 296.

[11] Li, Z.Y., et al., Numerical investigation of the inner profiles of ironmaking blast furnaces: effect of throat-to-belly diameter ratio. Metall. Mater. Trans. B-Proc. Metall. Mater. Proc. Sci., 2017. 48(1): p. 602-618.

[12] Dong, X.F., et al., Modelling of multiphase flow in a blast furnace: Recent developments and future work. ISIJ Int., 2007. 47(11): p. 1553-1570.

[13] Ariyama, T., et al., Recent Progress on Advanced Blast Furnace Mathematical Models Based on Discrete Method. ISIJ Int., 2014. 54(7): p. 1457-1471.

[14] Ueda, S., et al., Recent progress and future perspective on mathematical modeling of blast furnace. ISIJ Int., 2010. 50(7): p. 914-923.

[15] Yagi, J., Recent Progress in Fundamental and Applied Researches in Blast-Furnace Ironmaking in Japan. ISIJ Int., 1991. 31(5): p. 387-394.

[16] Kuang, S.B., Z.Y. Li, and A.B. Yu, Review on Modeling and Simulation of Blast Furnace. Steel Res. Int., 2018. 89(1): p. 1700071-1/25.

[17] Zhou, Z.Y., et al., Discrete particle simulation of particle-fluid flow: model formulations and their applicability. J Fluid Mech, 2010. 661: p. 482-510.

[18] Kuang, S.B., et al., Numerical study of hot charge operation in ironmaking blast furnace. Miner. Eng., 2014. 63: p. 45-56.

[19] Li, Z.Y., et al., Numerical investigation of novel oxygen blast furnace ironmaking processes. Metall. Mater. Trans. B-Proc. Metall. Mater. Proc. Sci., 2018. 49(4): p. 1995-2010.

[20] Dong, X.F., et al., Modeling of blast furnace with layered cohesive zone. Metall. Mater. Trans. B-Proc. Metall. Mater. Proc. Sci., 2010. 41(2): p. 330-349.

[21] Yang, K., et al., Numerical modeling of reaction and flow characteristics in a blast furnace with consideration of layered burden. ISIJ Int., 2010. 50(7): p. 972-980.

[22] Inada, T., et al., The effect of the change of furnace profile with the increase in furnace volume on operation. ISIJ Int., 2003. 43(8): p. 1143-1150.

[23] Austin, P.R., H. Nogami, and J. Yagi, A mathematical model for blast furnace reaction analysis based on the four fluid model. ISIJ Int., 1997. 37(8): p. 748-755.

[24] de Castro, J.A., et al., A six-phases 3-D model to study simultaneous injection of high rates of pulverized coal and charcoal into the blast furnace with oxygen enrichment. ISIJ Int., 2011. 51(5): p. 748-758.

[25] Yu, X.B. and Y.S. Shen, Computational fluid dynamics study of the thermochemical behaviors in an ironmaking blast furnace with oxygen enrichment operation. Metall. Mater. Trans. B-Proc. Metall. Mater. Proc. Sci., 2020. 51(4): p. 1760-1772.

[26] Yu, X.B. and Y.S. Shen, Numerical study of the influence of burden batch weight on blast furnace performance. Metall. Mater. Trans. B-Proc. Metall. Mater. Proc. Sci., 2020. 51(5): p. 2079-2094.
[27] Chew, S.J., P. Zulli, and A.B. Yu, Modelling of liquid flow in the blast furnace. Theoretical analysis of the effects of gas, liquid and packing properties. ISIJ Int., 2001. 41(10): p. 1112-1121.
[28] Zhang, S.J., et al., Modelling of the solids flow in a blast furnace. ISIJ Int., 1998. 38(12): p. 1311-1319.
[29] Austin, P.R., H. Nogami, and J. Yagi, A mathematical model of four phase motion and heat transfer in the blast furnace. ISIJ Int., 1997. 37(5): p. 458-467.
[30] Watakabe, S., et al., Operation trial of hydrogenous gas injection of COURSE50 project at an experimental blast furnace. ISIJ Int., 2013. 53(12): p. 2065-2071.