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Reaction Behavior in Lower Part of Blast Furnace with Hydrogen-Rich Gas Injection

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Nowadays, decarbonization in the iron and steel industry is a genuine responsibility. One potential method to reduce CO_2 emissions during ironmaking is the injection of hydrogen-rich gas into blast furnaces (BF). Natural gas (NG), containing high CH_4, is one of the hydrogen-rich gases that has been implemented in BF operations. However, maintaining the thermal balance during NG injection is one of the operational issues. This study aims to evaluate the reaction characteristics in the BF with NG injection. A simplified two-dimensional (2D) model is developed to simulate the thermal behavior and the distribution of reduction gases (CO and H_2) in the lower part of the BF. The results indicate that CH_4 utilization can be significantly improved with increased oxygen content to the raceway of a BF. These findings provide valuable insights for the development of the low-carbon ironmaking process.

Keywords: Hydrogen-rich gas injection, Blast furnace, Ironmaking, Decarbonization

1. INTRODUCTION

As climate change intensifies, reducing CO_2 emissions to the atmosphere becomes indispensable. For the sustainable development of the environment, China Steel Corporation (CSC) commits to reducing CO_2 emissions by 7% by 2025, reducing emissions by 25% by 2030, and achieving carbon neutrality by 2050. To accomplish the commitments, CSC proposes three strategies in the ironmaking process, including (1) using HBI as part of the raw material for the BF, (2) using hydrogen-rich gas as part of a reductant to reduce iron ore in the lower part of the BF, and (3) Co-production of steel and chemicals from the flue gases of BF, as illustrated in Fig.1[(1)].

The technology of hydrogen-rich gas injection is based on injecting hydrogen-containing gas, such as natural gas (NG), coke oven gas (COG), and hydrogen (H_2), into the BF. By using hydrogen as the reductant in the lower part of BF to replace part of the carbon-containing fuels (coke or coal), the total CO_2 emissions to the flue gas are accordingly reduced. Several study projects and plant tests on hydrogen-rich gas injection are currently underway. For instance, ThyssenKrupp in Germany tested H_2 injection into a BF through a single tuyere in 2019[(2)]. In Japan, the projects in Nippon Steel are divided into two parts. They conducted the COG

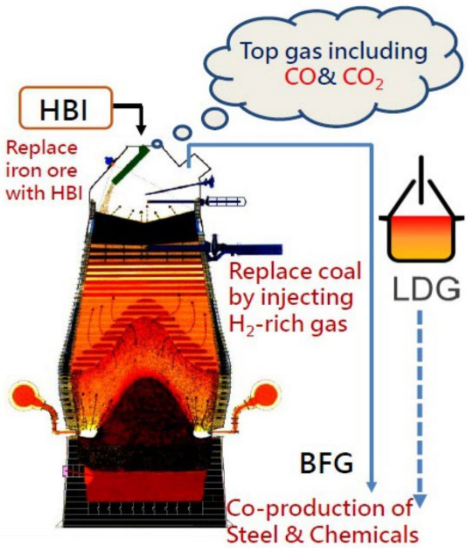


Fig.1. Strategy of low-carbon BF technology development in CSC[(1)]

injection experiment in an experimental blast furnace (EBF) in the COURSE 50 project and carried out the H_2 injection experiment in the SUPER COURSE 50 project. Nippon Steel is modifying the blowing equipment and plans to inject the COG into the operation BF in

2025[3]. JFE Steel is developing a carbon recycling blast furnace, which involves an oxygen blast furnace with CH_4 injection. The CH_4 is synthesized from the captured CO_2 of the BF and external carbon-free H_2[4].

In CSC, a test project for hydrogen-rich gas injection through a single tuyere into a BF is scheduled in 2024. The test project includes NG and COG injections. It is foreseen that when injecting a high flow rate of NG through the tuyere into the lower part of the BF, part of CH_4 might not be ignited due to insufficient mixing with blast air. This would lead to soot generation from CH_4 cracking accompanied by a strong endothermic reaction, which might locally decrease the BF heat[5]. To address this issue, some research teams are focusing on the designs of lance or injection methods to have a better mixing between NG and blast air[6].

As previously discussed, avoiding CH_4 cracking and soot formation during BF operations is essential to improve CH_4 combustion. Therefore, this study aims to investigate the reaction characteristics in the lower part of the BF with NG injection by using computational fluid dynamics (CFD) to have detailed information and reaction mechanisms about the thermal behavior, gas distribution in the BF, and combustion performance. The obtained results provide valuable insights for developing low-carbon BF technology.

2. METHODOLOGY

In the present work, commercial CFD software (Ansys Fluent) is used to develop a simplified 2D model for the simulation of reaction behavior in the lower part of the BF. The geometry is referred to the research work of Nogami[7], as demonstrated in Fig.2. In Nogami's study, a simplified 2D model was created to evaluate the reaction behavior in a BF with pulverized coal (PC) injection, demonstrating a good agreement with experimental results from a hot model. The geometry of the current 2D model includes a blowpipe, a tuyere, and a coke bed packed in the lower part of the BF.

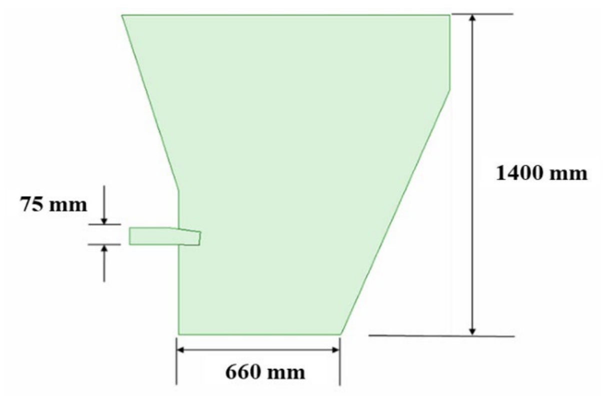


Fig.2. The geometry of the simplified BF model.

In the present model, the Eulerian multiphase model was employed to simulate the interactions among coke, blast air, and natural gas (NG) in the lower part of the BF. According to typical BF operations, the blast air was introduced at a temperature of 1473 K with 1 vol.% of moisture content. Detailed information about the parameters and boundary conditions is provided in Table 1.

The chemical reactions of NG combustion in the raceway region are simulated by using the Eddy Dissipation/Fine Rate model, which is commonly applied to hydrocarbon fuel combustion[8,9]. A user-defined solver[10] was developed to model the coke reactions, including combustion, steam gasification, and carbon solution loss reactions. The reactions considered in the model are listed in Table 2.

Table 1 Parameters and boundary conditions in the 2D model.

Parameter	Condition/ Property
Blast air	➢ Flow rate: 0.95 kg/s (@1473 K) ➢ Temperature: 1473 K ➢ Composition (%): 21% of O_2, 1 vol.% H_2O, and 78 vol.% of N_2
NG	➢ Injection rate: 0.066 kg/s ➢ Temperature: 300 K ➢ Composition: 97 vol.% of CH_4
coke	➢ Diameter: 30 mm ➢ Volume fraction: 0.6
Outlet condition	➢ Pressure out

Table 2 Chemical reactions in the raceway region of blast furnace.

Chemical reactions		
1	$H_{2\,(g)} + 0.5O_{2\,(g)} \rightarrow H_2O_{\,(g)}$	H_2 combustion
2	$CO_{(g)} + 0.5O_{2\,(g)} \rightarrow CO_{2\,(g)}$	CO combustion
3	$CO_{\,(g)} + H_2O_{\,(g)} \rightleftarrows CO_{2\,(g)} + H_{2\,(g)}$	Water gas shift reaction
4	$CH4_{\,(g)} + 2O_{2\,(g)} \rightleftarrows CO_{2\,(g)} + 2H_2O_{\,(g)}$	CH_4 combustion
5	$C_{\,(s)} + O_{2\,(g)} \rightarrow CO_{2\,(g)}$	Coke combustion
6	$C_{\,(s)} + CO_{2\,(g)} \rightarrow 2CO_{\,(g)}$	Carbon solution loss reaction
7	$C_{\,(s)} + H_2O_{\,(g)} \rightarrow CO_{\,(g)} + H_{2\,(g)}$	Steam gasification

3. RESULTS AND DISCUSSION

3.1 Temperature Distribution

The temperature profile in the lower part of the BF with NG injection is demonstrated in Fig.3. The region for NG ignition is located in front of the tuyere. This observation is different from the hydrogen injection case in Lin's work[10], where ignition occurred at the beginning of the blowing region due to the higher reaction rate of H_2 combustion.

In the coke bed, a lower temperature region (~1900 K) is obvious, consistent with the findings of Okosun et al.[6]. Okosun et al. reported that the reduction of gas temperature in the coke bed with NG injection is attributed to the endothermic reaction between coke and H_2O generated from NG combustion.

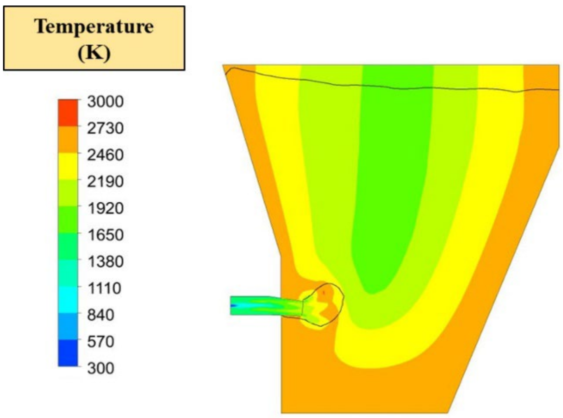


Fig.3. Temperature distribution in the lower part of BF with NG injection.

3.2 Gases Distributions in the Lower Part of the Blast Furnace

Fig.4. illustrates the gas distributions in the lower part of the BF with NG injection. The oxygen is all consumed in the raceway, accompanied by significant H_2O generation from NG combustion. Hydrogen (H_2) is primarily produced from steam gasification, with a molar fraction of approximately 0.12. Due to the endothermic reactions between H_2O and coke, the distribution of H_2 is similar to that of the temperature at a lower temperature area in the coke bed, as shown in Fig.3.

Regarding the thermal behavior in the BF with NG injection, it has been reported that the decrease in the raceway adiabatic flame temperature (RAFT) with NG injection is significantly higher than that with coal injection. For instance, the changes in RAFT with the injection of 1 kg/tHM of NG and coal are -7.6 °C and -2.7 °C, respectively[11].

Notably, due to the incomplete combustion of NG in the raceway, the molar fraction of CH_4 remains around 0.06-0.07. As mentioned in the introduction, the presence of unburned CH_4 could lead to non-uniform thermal distributions in the lower part of the BF. To maintain the RAFT temperature and to improve the combustion performance of NG, BFs with NG injection typically operate with a higher oxygen supplement[5,11].

3.3 Effects of O_2 Enrichment on CH_4 Utilization

The effects of O_2 enrichment on CH_4 utilization are examined and discussed in this section. The simulation results indicate that the gas temperature in the lower part of the BF increases as O_2 supplementation from the air is raised from 0% to 3% (Fig.5). This observation is consistent with the work of Peng[12]. Peng et al. simulated the combustion of reduction gas (15.3% H_2 and 65.9% CO) and coal under various O_2 content conditions (21-50%) in the tuyere and raceway regions. They observed a significant increase in high-temperature areas at higher O_2 content levels.

To evaluate the performance of CH_4 combustion, an index of CH_4 utilization was introduced, as expressed in Eq.(1).

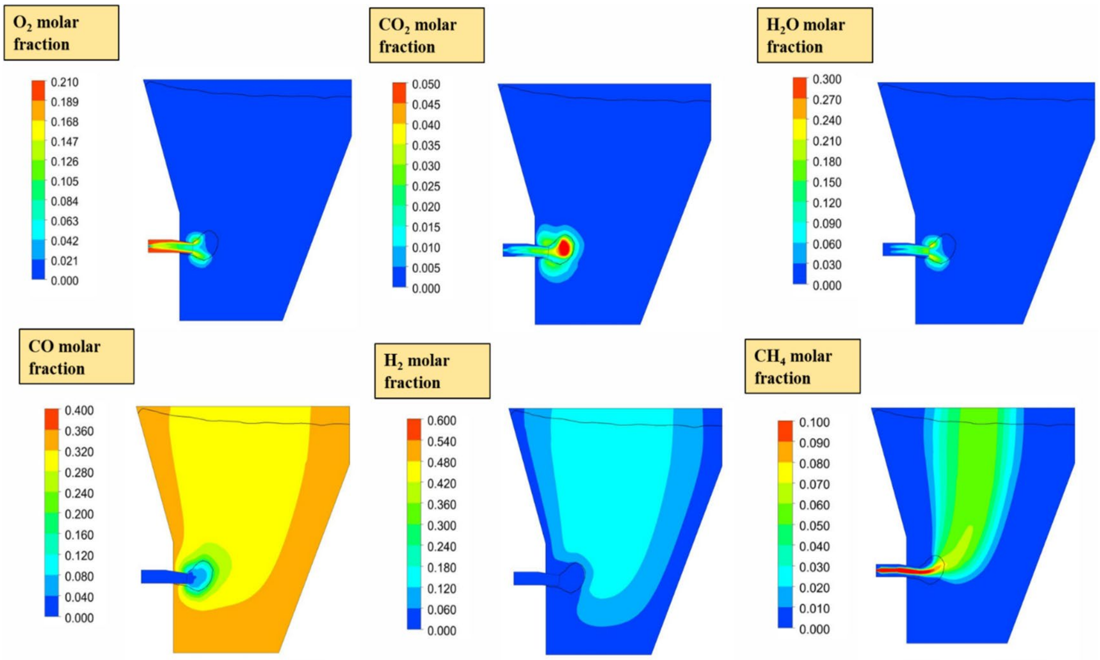


Fig.4. Gas distributions in the lower part of BF with NG injection.

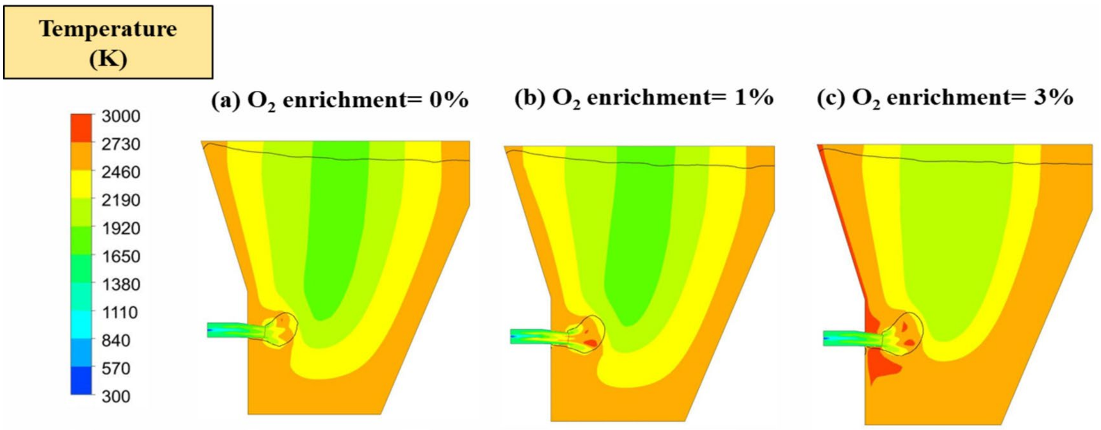


Fig.5. Temperature distribution in the lower part of BF with NG injection at oxygen enrichment of (a) 0 % (b)1% and (c) 3%.

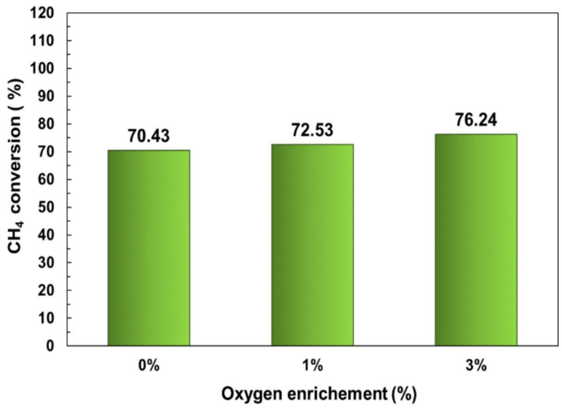
$$\text{CH}_4 \text{ ulitilation } (\%) = \frac{\text{Inlet mass of CH}_4 - \text{Oulet mass of CH}_4}{\text{Inlet mass of CH}_4} \times 100\% \quad \text{.......} (1)$$

In Fig.6a., it is found that the CH_4 utilization can be significantly improved from 70.43 % to 76.24 % with increasing O_2 supplementation (approximately 8.2 % increment). Furthermore, due to enhanced combustion performance, there is a slight increase in the proportions of reduction gases CO and H_2 at the outlet of the lower part of the BF, as illustrated in Fig.6b**.**

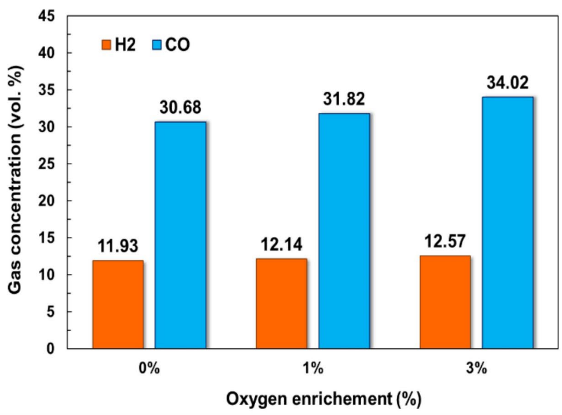
4. CONCLUSIONS

The simplified 2D model of the lower part of BF, comprising a blowpipe, raceway, and coke bed, has been successfully developed to investigate the reaction behavior with NG injection. The study results are summarized as follows:

1. The profile of gas temperature is evaluated to describe the thermal behavior in the BF with NG injection. A significantly lower temperature zone, primarily attributed to the endothermic reaction between coke and H_2O, is observed.



(a)



(b)

Fig.6. (a) CH_4 and (b) gas concentration of CO and H_2 at the outlet of the lower part of BF with various oxygen enrichment.

2. According to the profile of CH_4, 7-8 vol.% of unburned CH_4 is found, suggesting the incomplete combustion of NG under the current boundary conditions in the model.
3. Increasing O_2 content to the raceway is an efficient method to enhance the combustion performance of NG. At 3% of O_2 supplementation, the CH_4 utilization is 76.24 %, representing 8.2 % of increment.

REFERENCES

1. https://www.csc.com.tw/csc_e/ss/pst/pst_index2.html.
2. https://www.thyssenkrupp-steel.com/en/newsroom/press-releases/thyssenkrupp-steel-concludes-first-test-phase-successfully.html.
3. https://www.nipponsteel.com/en/news/20230804_200.html.
4. Sato, M., Fukada, K. & Hasegawa, S. Recent Development of Ironmaking Technology in JFE Steel toward Carbon Neutrality. JFE Technical Report 28, 1–8 (2022).
5. Babich, A. Blast furnace injection for minimizing the coke rate and CO2 emissions. Ironmaking & Steelmaking 48, 728–741 (2021).
6. Okosun, T. et al. On the impacts of pre-heated natural gas injection in blast furnaces. Processes 8, 771 (2020).
7. Nogami, H., Yamaoka, H. & Takatani, K. Raceway design for the innovative blast furnace. ISIJ international 44, 2150–2158 (2004).
8. Okosun, T., Nielson, S. & Zhou, C. Blast furnace hydrogen injection: Investigating impacts and feasibility with computational fluid dynamics. JOM 74, 1521–1532 (2022).
9. Farajzadeh, E., Zhuo, Y. & Shen, Y. Numerical investigation of the impact of injecting coke oven gas on raceway evolution in an ironmaking blast furnace. Fuel 358, 130345 (2024).
10. Lin, B.-J., Du, S.-W., Tsai, C.-H. & Hsu, S.-Y. Characteristics of Reactions in Raceway Zone of Blast Furnace with Hydrogen Injection. Combustion Quarterly 120, 4-11 (2023).
11. Geerdes, M., Chaigneau, R. & Lingiardi, O. Modern blast furnace ironmaking: an introduction (2020). (Ios Press, 2020).
12. Peng, X. et al. Influence of reducing gas injection methods on pulverized coal combustion in a medium oxygen-enriched blast furnace. Jom 73, 2929-2937 (2021).