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Simulation of Blast Furnace Operation with Intensive Hydrogen Injection

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Recent years various trials to decrease carbon dioxide emission from iron and steelmaking industries have been made. One of these trials is utilization of hydrogen in blast furnace process, and this study performed numerical simulation of blast furnace operation with hydrogen injection through tuyere. The simulations were carried out under the conditions of constant bosh gas flow rate, adiabatic flame temperature and hot metal temperature. The simulation results showed that the temperature level in the stack part was decreased with increase in the hydrogen injection ratio. This resulted in the lowering of the top gas temperature and retarded the reduction of iron oxide especially one of magnetite. The injection of the hydrogen remarkably decreased the coke rate. The converted reducing agent rate, that is sum of coke rate and six times (molecular weight ratio of carbon to hydrogen gas) as hydrogen rate showed small change. Although this decrease in coke rate deteriorated the permeability of the burden materials in the furnace, pressure drop in the furnace was reduced. Since the molar flow rate of the reducing gas was kept constant, the decrease in the gas density due to the increase in the hydrogen content was mainly considered to lead the decrease in the pressure drop. The water gas shift reaction played an important role in the generation of the field of gas composition, thus this reaction has to be carefully discussed for further utilization of hydrogen in blast furnace.

KEY WORDS: blast furnace; hydrogen; numerical simulation; injection.

1. Introduction

In recent years iron and steelmaking industries have received strong social pressure to reduce carbon dioxide emission. The primary energy source and reducing agent of these industries are coal, and the carbon in the coal is finally released as CO₂ to the environment. In the integrated route of steelmaking, the ironmaking processes that convert iron oxides in the ore to metallic iron consume about 70 percent of the energy input to the steel works. Thus various efforts have been made to reduce energy consumption in the ironmaking processes. One of the approaches to reduce CO₂ emission is effective use of hydrogen as a reducing agent. Reduction reaction of iron oxide by hydrogen gas generates only H₂O as gaseous product, while the reduction by carbon monoxide generates CO₂. Therefore the replacement of carbon with hydrogen as a reducing agent is expected to decrease CO₂ emission from the ironmaking processes. The authors performed numerical simulation of blast furnace operation with injection of hydrogen bearing materials¹⁾ and its results were analyzed through heat and mass balance analysis²⁾ on ironmaking system. These analyses showed

that the utilization of hydrogen bearing materials reduced the carbon dioxide emission. Contrariwise the utilization of hydrogen in ironmaking processes is apprehended to deteriorate the process operation from the following issues. The hydrogen reduction of iron oxide is endothermic reaction while the reduction by CO is exothermic, namely the reaction heat of $\text{Fe}_2\text{O}_3 + 3 \text{H}_2 \rightarrow 2 \text{Fe} + 3 \text{H}_2\text{O}$ is 100 kJ (endothermic, at 298 K) while one of $\text{Fe}_2\text{O}_3 + 3 \text{CO} \rightarrow 2 \text{Fe} + 3 \text{CO}_2$ is -23.5 kJ (exothermic, at 298 K). Furthermore the water gas reaction, which is an endothermic reaction between carbon and water vapor ($\text{C} + \text{H}_2\text{O} \rightarrow \text{CO} + \text{H}_2$), is expected to increase. Therefore hydrogen ironmaking is possibly to require more energy to compensate these endothermic reaction heats. In blast furnace, coke as a reducing agent and iron bearing materials are charged alternately and layer-by-layer structure is formed. Although the coke layer usually has higher permeability to the gas, the coke layer is thinned when the reducing agent is replaced by hydrogen. Thus extensive utilization of hydrogen is expected to deteriorate the flow of reducing gases. From such background this study discusses on hydrogen injection operation of blast furnace through numerical experiments using the kinetic based operation simulator.

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2. Simulation of Blast Furnace Operation

2.1. Mathematical Model

To simulate effect of hydrogen injection into tuyere on blast furnace operation, a blast furnace simulator, which uses theories of multi-phase fluid dynamics, reaction kinetics, and transport phenomena as its fundamental framework, is used.³⁻⁶⁾ This simulator consists of coupled partial differential equations that include conservation equations of momentum, heat, chemical species and continuity for five phases, namely gas, charged granular materials, molten iron, liquid slag and powder. All conservation equations take into account inter-phase interactions, in other words exchanges of mass, heat and momentum. Simultaneous solution of these equations gives in-furnace distributions of temperature, motion, pressure, concentrations of chemical species, rates and ratios of reactions, and so on as well as overall operation indices like production, reducing agent rate, gas utilization, *etc.*. Reaction kinetic parameters for the water gas reaction and the solution loss reaction have been modified as shown in previous study⁷⁾ suitable for high combustion temperature of hydrogen.

2.2. Examined Condition

An all coke operating condition summarized in **Table 1** is used as a standard condition. In this condition, flow rate, temperature and oxygen enrichment are 7897 Nm³/min, 1200°C and 2.5%, respectively. Production and coke rate are 10400 t/d and 498 kg/thm. To examine the effect of hydrogen injection, blast condition is adjusted as follows. First, a part of blast air, which contains moisture of 39 g/Nm³, is replaced with hydrogen, and then oxygen is added to keep adiabatic flame temperature (2597 K). Finally, total blast flow rate is adjusted to maintain bosh gas flow rate. With these constant bosh gas temperature and flow rate, sensible heat supplying rate to the reaction zone of the blast furnace is kept almost constant. Note that this heat supplying rate is merely time basis and not on the production basis. The blast flow rate and composition, and bosh gas composition are summarized in **Fig. 1**. The maximum hydrogen content in the blast gas is about 43 mol-%, the blast flow rates slightly increases with addition of hydrogen. For bosh gas composition, CO concentration slightly decreases and N₂ concentration decreases with hydrogen addition. The bosh gas flow rate for all conditions is 7.414 kmol s⁻¹. Furthermore burden charging condition, namely ore to coke ratio, is adjusted to keep hot metal temperature (1500°C).

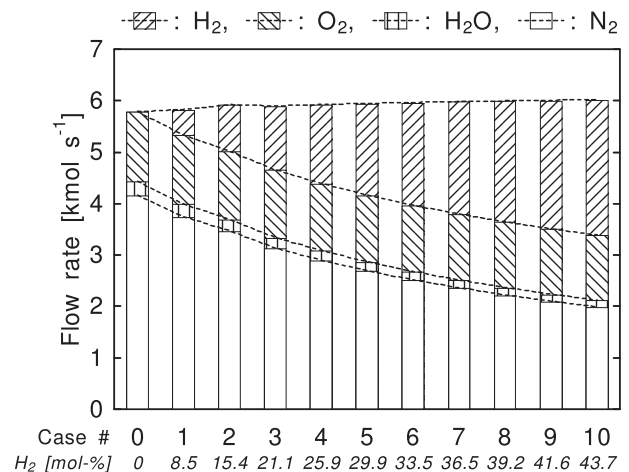
3. Results

Figure 2 shows variation of in-furnace solid temperature distribution with hydrogen addition. In stack part tempera-

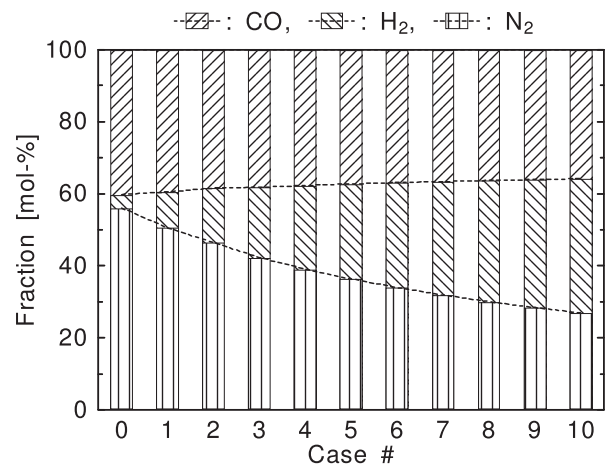
ture level decreases and isotherms from 200 to 600°C remarkably shift downward with the hydrogen injection. Contrarily cohesive zone height, which is determined as a region between 1200 and 1400°C, shows small variation. Consequently the temperature gradient above the cohesive zone gets steeper as the blast hydrogen increases. With this variation of temperature distribution, the top gas temperature lowers with increase in the hydrogen injection as shown in **Fig. 3(a)**. Production rate of hot metal increases with the hydrogen injection rate as shown in **Fig. 3(b)**.

Figure 4 shows variation of distribution of overall reduction degree. In the stack part, contour lines of reduction degree shift downward with increase in the hydrogen injection, especially distance between contour lines of 10 and 20% become wider. The location of 10% degree is regardless of hydrogen injection rate, thus the reduction of Fe₃O₄ is mainly retarded. It is considered that this delay of the reduction is mainly caused by the temperature lowering in the stack part because the total concentration of reducing gases increases with increase in the hydrogen injection ratio as shown in **Fig. 1(b)**. Contrarily distance among the contour lines in the region above the cohesive zone get narrower, and the reduction in this region proceeds quicker under higher hydrogen injection conditions.

Figure 5 shows the ratio of hydrogen reduction to the



a) Blast flow rate



b) Bosh gas composition

Fig. 1. Blast and bosh gas conditions.

Table 1. Major operating conditions for standard case.

Inner volume	4 359 m ³
Productivity	10 400 t/d
RAR (CR)	498 kg/thm
Blast volume	7 897 Nm ³ /min
Blast temp.	1 200°C
O ₂ enrichment	2.5%

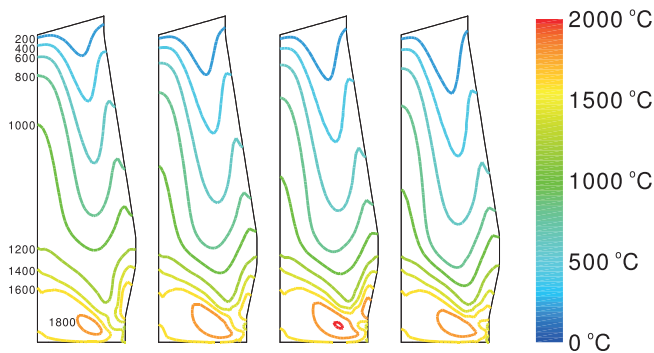
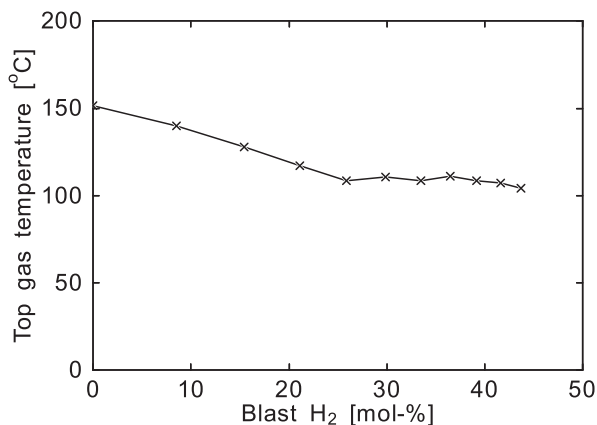
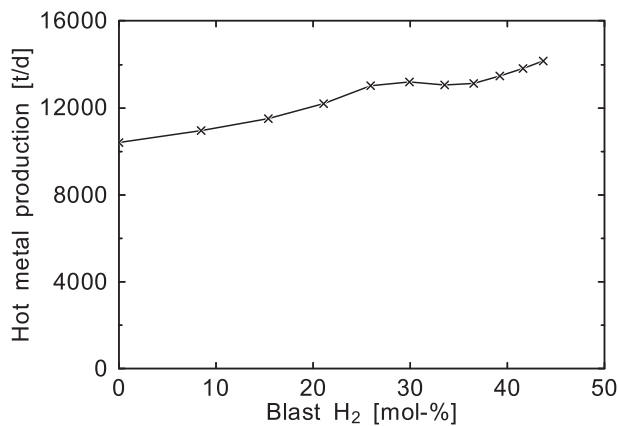


Fig. 2. Variation of solid temperature distribution with hydrogen injection ratio.



a) Top gas temperature



b) Hot metal production

Fig. 3. Variations of top gas temperature and hot metal production with hydrogen injection ratio.

total reduction for each step of reduction. The rates of reductions are summed up over the furnace separately by the steps and reducing gas, then the ratio of hydrogen reduction for each step is calculated. In all steps the hydrogen reduction ratio increases with increase in hydrogen injection. For reduction of Fe_2O_3 , most part of Fe_2O_3 is reduced by the hydrogen even hydrogen injection rate is small. The kinetic parameters, namely effective diffusivity and chemical reaction rate constant, for hydrogen reduction for this step are higher about two orders compared to CO reduction.⁸⁾ This is considered as one of the reasons for such high ratio in the low hydrogen injection rate. The other two steps, the hydro-

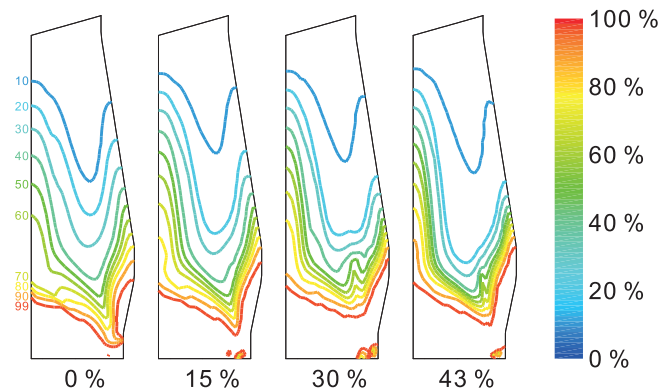


Fig. 4. Variation of distribution of overall reduction degree with hydrogen injection ratio (Contours from 10 to 90% with 10% interval and 99%).

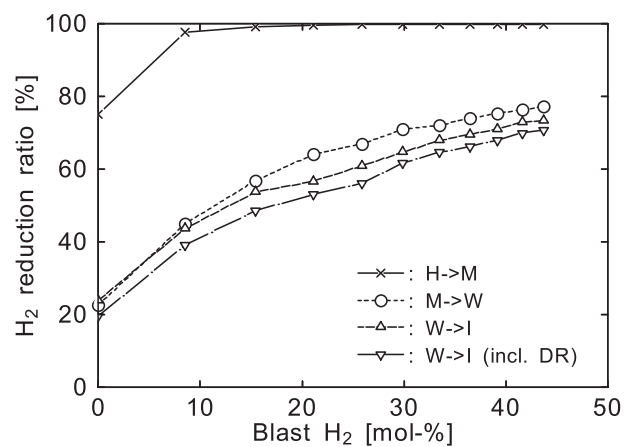
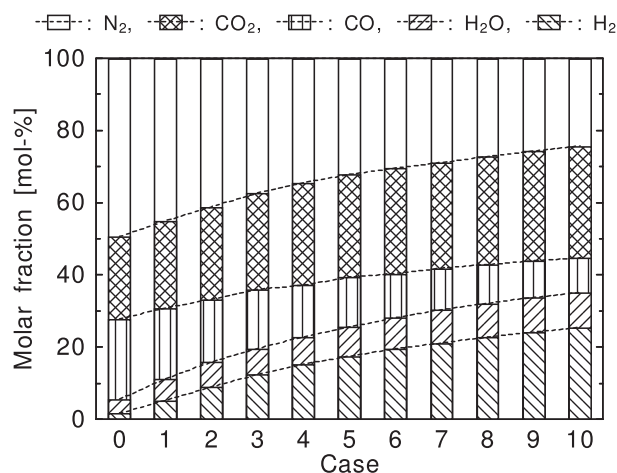


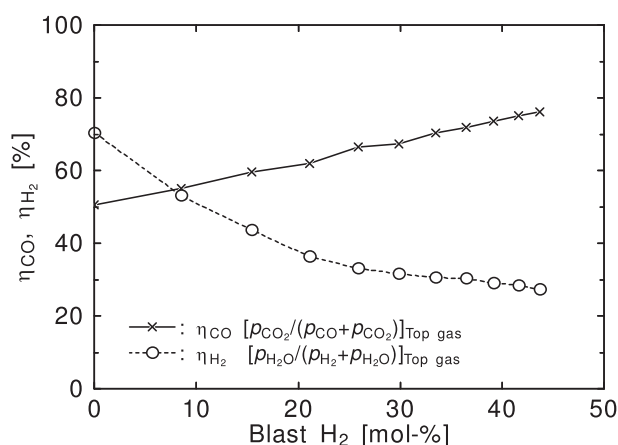
Fig. 5. Variation of hydrogen reduction ratio.

gen reduction ratios increase with increase in blast hydrogen ratio, and they reach about 70–80% when the hydrogen content is 40%. The reduction of Fe_xO proceeds through indirect reductions by CO and H_2 and direct reduction (DR). With taking into account the direct reduction, the ratio of the hydrogen reduction in this step shows small change.

Figure 6 shows variations of top gas composition and gas utilization degrees with the hydrogen injection ratio. With increase in the hydrogen injection ratio, the nitrogen content in the top gas decreases due to the nitrogen content in the blast gas. Total amount of hydrogen bearing species, namely hydrogen and water vapor, increases with increase in the hydrogen injection ratio. Both species increase and hydrogen shows higher increasing rate to the hydrogen injection ratio. Regarding carbon monoxide and carbon dioxide, total amount show small change regardless of the hydrogen injection ratio. The carbon monoxide concentration decreases while the carbon dioxide concentration increases with the increase in the hydrogen injection ratio. Figure 6(b) shows the variation of the gas utilization degrees. With above-mentioned variation of the top gas composition, utilization degree of carbon monoxide increases and one of hydrogen decreases with the increase in the hydrogen injection ratio. These variations are opposing to the tendency of reduction shown in Fig. 5 that is the increase in the hydrogen reduction. The increase in the ratio of hydrogen reduction is expected to lead the increase in hydrogen utilization and the



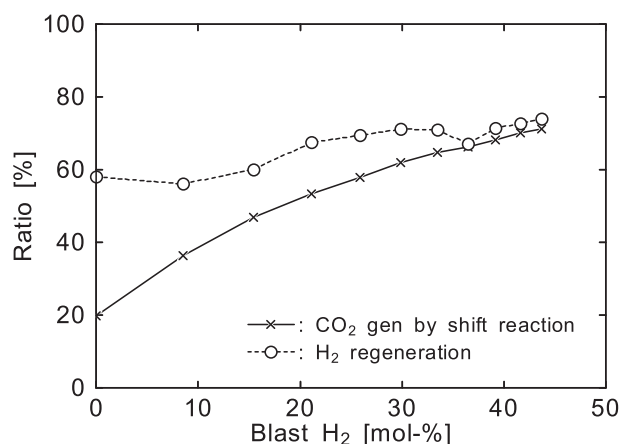
a) Top gas composition



b) Gas utilization degree

Fig. 6. Variations of top gas composition and gas utilization degree with hydrogen injection ratio.

decrease in utilization of carbon monoxide. Thus the reactions other than gaseous reduction of iron oxide are expected to occur. The reactions in the blast furnace that include carbon monoxide and hydrogen are: 1) solution loss reaction ($\text{CO}_2 + \text{C} \rightarrow 2 \text{CO}$), 2) water gas reaction ($\text{H}_2\text{O} + \text{C} \rightarrow \text{CO} + \text{H}_2$) and 3) water gas shift reaction ($\text{CO}_2 + \text{H}_2 \rightleftharpoons \text{CO} + \text{H}_2\text{O}$). The former two reactions tend to decrease CO utilization. Third reaction, the water gas shift reaction, can proceed both direction in the blast furnace depending on the gas composition and temperature. When this reaction proceeds to left hand side, gaseous composition apparently varies to decrease the hydrogen utilization and increase the carbon monoxide utilization. The comparison of local gaseous composition and equilibrium constant reveals that the water gas shift reaction proceeds to the right hand side (generation of CO and H_2O) in the region from about 1000°C down to the cohesive zone. The temperature of the lower temperature side of this region decreases with the hydrogen injection ratio that is about 1100°C in the standard condition and 900°C in the 43% hydrogen case, while one of the high temperature side show little change. In the stack part above this region, the water gas shift reaction proceeds to the left hand side that generates carbon dioxide and hydrogen. **Figure 7** shows the gas conversion ratios by the water gas shift reac-


Fig. 7. Variations of gas conversion ratio with hydrogen injection ratio.

tion. The ratio of carbon dioxide generation in this figure is defined as the ratio of net carbon dioxide formation by the shift reaction to the total carbon dioxide generation by the shift reaction and the reduction. The ratio of hydrogen regeneration is determined as the ratio of net consumption of water vapor by the shift reaction to the H_2O generation by the hydrogen reduction of the iron oxide. The generation ratio of carbon dioxide increases with increase in the hydrogen injection ratio, and reaches about 70% in the case with the highest hydrogen injection ratio. Thus the major part of carbon dioxide is generated by the shift reaction under intensive hydrogen injection operation. The hydrogen regeneration ratio gradually increases with increase in the hydrogen injection ratio. More than a half of water vapor formed by the reduction is regenerate to the hydrogen through the water gas shift reaction. Therefore the water gas shift reaction strongly relates the variation of top gas composition under intensive hydrogen injection operation of blast furnace, and the effect of the shift reaction should be carefully discussed.

The other reactions show the following variations. The amounts of the solution loss reaction, the direct reduction decrease with increase in the hydrogen injection ratio. The decrease in the former reaction is brought by the shrinkage of the reaction zone due to the steep temperature distribution above the cohesive zone, and the latter is caused by the higher reaction rate of the indirect reduction by the hydrogen. The decreases in these reactions to the hydrogen injection ratio get small in the range of the hydrogen ratio higher than about 30%. The amount of the water gas reaction once increases then decreases with increase in the hydrogen injection ratio. It is considered that the decreases in the endothermic reaction heats of these reactions support the progress of the reduction reactions and the heating up of burden materials while the temperature decrease and the retardation of the reduction reaction occurs in the stack region under higher hydrogen injection conditions.

Figure 8 shows the variations of reducing agent rates with the hydrogen injection ratio. Due to the difference in the molecular weight between hydrogen gas and carbon, converted reducing agent rate is defined as the sum of coke rate and six times of hydrogen injection rate. The converted reducing agent rate is almost constant regardless of the

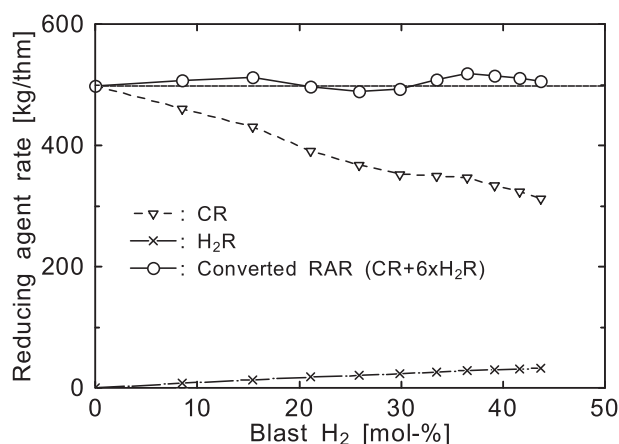


Fig. 8. Variation of reducing agent rates with hydrogen injection ratio.

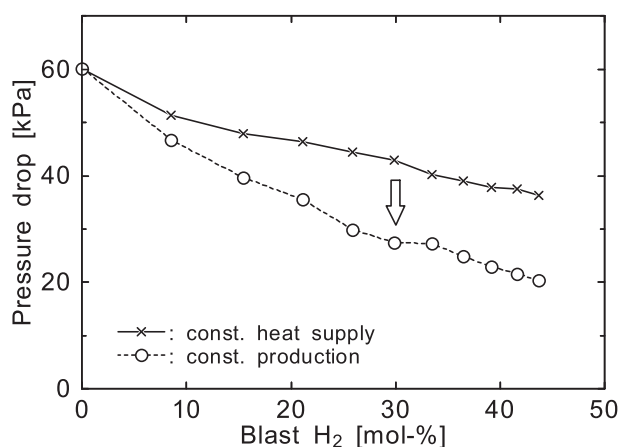


Fig. 9. Variation of pressure drop with hydrogen injection ratio.

hydrogen injection ratio. The coke rate decreases almost linearly to the hydrogen injection ratio while the hydrogen injection rate increases almost linearly. Thus the carbon consumption, which is finally released as carbon dioxide, becomes smaller by the use of hydrogen.

Figure 9 shows the variation of pressure drop in the furnace with the hydrogen injection ratio. The pressure drop shown in this figure is of packed bed in the furnace that is defined as the pressure difference between the computation cell at burden surface and one in front of tuyere nose. The variation of the pressure drop in the results shown so far is plotted by the cross mark. The pressure drop decreases with the increase in the hydrogen injection ratio despite of the decrease in the coke layer which has higher permeability than the ore layer that is expected from the variation of coke rate shown in Fig. 8. The molar flow rate of the bosh gas is kept constant in these calculations, thus the following two matters are expected to reduce the pressure drop. One is the decrease in the gas velocity due to the decrease in the stack

temperature, and the other is decrease in the gas density due to the increase in the hydrogen content. One of the major pressure drops is generated in the cohesive zone, and the gas velocity in this zone is almost constant because the temperature level of the cohesive zone is common throughout the simulations. Thus the gas density decrease is considered as the main reason of the decrease in the pressure drop. As shown in Fig. 3(b), in the above-mentioned series of examined condition, the hot metal production rate increases with the hydrogen injection ratio while the heat supply from the combustion zone is kept almost constant. Therefore, further decrease in the pressure drop is expected when the hot metal production rate is kept constant. The variation of the pressure drop under constant production rate conditions is plotted as circle mark in Fig. 8. In this series the blast flow rate is decreased with the hydrogen injection ratio to maintain the hot metal production ratio. The decrease in the pressure drop is larger than that in the constant heat supply condition as expected.

4. Conclusions

Blast furnace operations with intensive hydrogen injection were numerically examined in this study. In all examined cases, bosh gas flow rate and adiabatic flame temperature were kept constant regardless of hydrogen injection ratio by adjusting blast flow rate and oxygen addition. Simulation results under intensive hydrogen injection operation showed;

- (1) The temperature level in the stack part is decreased and it leads the lowering of the top gas temperature and delay of reduction reaction in the stack part.
- (2) The coke rate remarkably decreases with injection while the converted reducing agent rate shows small change.
- (3) Increase in the hydrogen content in the reducing gas decreases the pressure drop in the furnace despite of the decrease in higher permeable coke layer.
- (4) The water gas shift reaction becomes remarkable, and should be carefully discussed.

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