Prediction of Pre-reduction Shaft Furnace with Top Gas Recycling Technology Aiming to Cut Down CO₂ Emission

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Top gas recycling is considered as one of the highest potential technologies to improve reduction efficiency and correspondingly to reduce carbon consumption. As a typical nitrogen free ironmaking process, pre-reduction shaft furnace of COREX® process (COREX® shaft furnace) for short is suitable to adopt the technology aiming to cut down CO₂ emission. Under the premise of constant total injection volume, three kinds of reducing gas injection methods are numerically studied by employing a two-dimensional mathematical model. The method that 20% of total reducing gas in volume fraction is blasted through normal inlet (NI) while the rest through down pipe inlet (PI) rather than deadman inlet (DI) could apparently improve gas flow in the inactive zone located near the bottom direct reduced iron (DRI) outlet, thus increasing DRI reduction degree to 61% under present calculation conditions. Meanwhile, either decreasing the vertical height of PI or increasing its diameter makes further improvement on furnace efficiency. After adopting top gas recycling to the shaft furnace by NI+PI method with optimal parameters, CO utilization ratio reaches above 46% when DRI reduction degree correspondingly increases by 12%, what’s more, CO₂ emission from the whole process is reduced by about 540 Nm³/tHM. The results prove that top gas recycling technology promotes reduction efficiency inside shaft furnace and greatly reduces the greenhouse gas emission, which will contribute to suppressing global warming.

KEY WORDS: shaft furnace; mathematical model; injection method; top gas recycling; CO₂ emission.

1. Introduction

Reducing CO₂ emission from iron and steel industry is regarded as not only a countermeasure to deal with global warming problem, but also a solution to the sustainable development of the industry itself. In recent years, some joint projects are proposed to develop technologies against high energy consumption as well as tremendous greenhouse gas emission in steel plants, such as Ultra-low CO₂ Steelmaking (ULCOS) in Europe,1) CO₂ Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50 (COURSE 50) in Japan,2) Saving One Barrel of Oil per Ton: A New Roadmap for Transformation of Steelmaking Process (SOBOT) in North America.3) Besides, China, as the largest manufacturer of crude steel in the world, also makes great efforts to minimize CO₂ emission.4) COREX® process, developed for independence of coking coal and meeting environmental demands,5) realized its largest-scale production in terms of C-3000 in Baosteel. However, it failed to achieve the original target with the fuel ratio reaching as high as about 1 000 kg/t HM.6) So it is urgently to make further progress of present COREX® process by adopting novel technologies to improve furnace efficiency as well as reduce CO₂ emission.

According to the previous researches on blast furnace (BF), reducing gas injection into the upper shaft was proposed and proved to reduce coke rate. Both Kobayashi et al. and Miyashita et al. concluded that the gas should contain less CO₂ and H₂O and had to be heated above 1 000°C to satisfy the staged heat balance by both theoretical and experimental methods.7,8) Stack gas injection was also applied to oxygen enriched BF and found to increase gaseous reduction in a relatively low temperature region and to decrease carbon solution loss reaction in order to save coke.9–13) As far as the injection gas was concerned, Yatsuzuka et al. developed Fuji-Texaco-Gas (FTG) injection process combining a partial oxidation process to produce it from the available fuel oil outside the furnace,14,15) while Buchwalder et al. developed Hot Gas Generators (HGG) to produce it from natural gas.16) On the contrary, top gas recycling process (NKG), developed by Nishio and Miyashita et al., produced shaft injection gas by recycling top gas instead of combusting fuel materials aiming to further reduce fuel consumption.17,18) The prediction by both numerical simulation and trial BF operation indicated that the shaft injection of hot reducing gas, in which CO₂ was stripped from the recycled gas, led to an increase in production and simultaneously a decrease in fuel rate.19–23) As a whole, top gas recycling technology combining shaft injection was proved to make positive contribution to cutting down CO₂ emission from BF. On the other hand, although the utilizations of COREX® shaft furnace export gas were generally discussed for elec-
tric power generation, chemical products and BF shaft injection,24–30) as a typical nitrogen-free process, it is much more applicable to capture and remove CO2 and H2O in the top gas and to recycle it for re-injection. Meanwhile, due to the fact that COREX® process is consist of two individual metallurgical furnaces with different energy demands, which will be discussed later, the recycled gas can play the role to narrow the gap as the cooling gas. In addition, the shaft furnace also differs from BF in gas composition, distribution and furnace structure. Given above reasons, it is worth studying the optimal parameters of shaft furnace operation with top gas recycling in order to improve furnace efficiency as well as reduce greenhouse gas emission, aiming to suppress global warming.

In present work, a two-dimensional mathematical model is established based on gas and solid two fluid phases. After summarizing COREX® shaft furnace characteristics,31) reducing gas injection through both man-made deadman and down pipe are simulated with the validated model and the results are compared with respect to gas flow volume distribution ratio (VDR). With the optimal injection parameters, shaft furnace performance under top gas recycling is further predicted.

2. Brief Summary of COREX® Shaft Furnace Characteristics

According to the authors’ previous work,31) the characteristics of COREX® shaft furnace have been summarized in terms of the following three aspects as shown in Fig. 1.

2.1. Reducing Gas Distribution

Figure 1(a) demonstrates the gas velocity distribution inside the furnace. Since the reducing gas is introduced through side circumferentially distributed inlets on the wall, it reaches neither the center nor the bottom of the furnace, thus leaving several inactive zones, especially those near the bottom. The gas velocity is less than 0.5 m/s exerting negative influences on both iron ore reduction and reducing gas utilization.

2.2. Iron Ore Reduction

In Fig. 1(b), it is obvious that the reduction rate from wustite (FeO) to metallic iron (Fe) by CO is the highest around the inlet, and then begins to decrease gradually as the gas ascending. However, the rate gradient is much greater in the lower part of the furnace than in the upper part as a result of the different flow rate of the reducing gas shown in Fig. 1(a). In addition, the utilization ratio of CO is calculated as 40.9% based on the corrected expression of ηCO given by Eq. (1). It can be imagined how huge carbon resource is wasted in the typical nitrogen-free ironmaking process.

\[
\text{Corrected } \eta_{CO} = \frac{m_{CO, top \text{ gas}} - m_{CO, reducing \text{ gas}}}{m_{CO, top \text{ gas}}} = \frac{M_{CO}}{M_{CO}} \cdot \frac{m_{CO, top \text{ gas}} - m_{CO, reducing \text{ gas}}}{m_{CO, top \text{ gas}} - m_{CO, reducing \text{ gas}}} \tag{1}
\]

2.3. Furnace Structure

Although shaft furnace has reduction behaviors similar to that in the lumpy zone of BF, it has independent process characteristics and the principal gas distribution can be controlled by selecting proper locations of inlets. As is shown in Fig. 1(c), besides NI, the reducing gas can be introduced through DI to promote central gas flow, or PI to further strengthen peripheral gas flow. Therefore, it is likely to develop bi-injection methods to arrange various reducing gas distribution inside the furnace.

Based on above summaries, besides single NI injection method, two kinds of bi-injection methods are proposed to study the optimal reducing gas distribution inside the furnace. NI+DI bi-injection method: the reducing gas is blasted into the shaft furnace through the central DI and side NI simultaneously and NI+PI bi-injection method: the reducing gas is introduced through the side NI and PI located at different heights. The schematic diagrams of all three kinds of reducing gas injection methods are shown in Fig. 2 where single NI injection method is assumed as base case.

3. Numerical Prediction and Results on Different Injection Methods

3.1. Model Formulation

Both gas and solid phases considered in present work are
In Eq. (2), \( p \) represents the phase being considered, the effective diffusive transfer coefficient \( \Gamma \) varies with respect to different variables \( \phi \). As is clarified in Table 1, both the continuity and species equations have mass source due to chemical reactions. The reduction rates are calculated based on the three-interface unreacted core model, while the water gas shift reaction rate is considered with rate equations determined by Ranz-Marshall equation and enthalpy change accompanying chemical reactions. The other relevant formulations for phase properties and chemical reaction enthalpy have been previously published.

The iron-blending materials (66% TFe in mass fraction) is assumed to be fluids and are modeled by the general conservation equations. The species in the gas phase are CO, CO\(_2\), H\(_2\) and H\(_2\)O while those in the solid phase are Fe\(_2\)O\(_3\), FeO, Co and Fe. The conservation equations of continuity, momentum, energy and species transport for both phases in steady state could be described by Eq. (2).

\[
\nabla(p \cdot \rho \cdot \phi \cdot \nabla \bar{v}_p) = \nabla(p \cdot \Gamma \cdot \nabla(\phi)) + S_\phi \quad \ldots \ldots \quad (2)
\]

Table 1. Variables considered in Eq. (2).

<table>
<thead>
<tr>
<th>Classification</th>
<th>Term</th>
<th>Expression</th>
<th>Ref.</th>
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<td>chemical reactions</td>
<td>( R_1 )</td>
<td>( 3\text{Fe}_2\text{O}_3 + \text{CO} \rightarrow 2\text{Fe}_2\text{O}_3 + \text{CO}_2 )</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>( R_2 )</td>
<td>( \text{Fe}_2\text{O}_3 + \text{CO} \rightarrow 3\text{FeO} + \text{CO}_2 )</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>( R_3 )</td>
<td>( \text{FeO} + \text{CO} \rightarrow \text{Fe}_2\text{O}_3 + \text{CO} )</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>( R_4 )</td>
<td>( 3\text{Fe}_2\text{O}_3 + \text{H}_2 \rightarrow 2\text{Fe}_2\text{O}_3 + \text{H}_2\text{O} )</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>( R_5 )</td>
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<td></td>
<td>( R_6 )</td>
<td>( \text{FeO} + \text{H}_2 \rightarrow \text{Fe}_2\text{O}_3 + \text{H}_2\text{O} )</td>
<td>33</td>
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<tr>
<td></td>
<td>( R_7 )</td>
<td>( \text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2 )</td>
<td>34</td>
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Table 2. Schemes designed for either NI+DI or NI+PI injection method with VDR ranging from 0 to 100%.

<table>
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<tr>
<th>Scheme</th>
<th>VDR/%</th>
<th>Gas Volume Fraction/%*</th>
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<tr>
<td></td>
<td></td>
<td>NI</td>
</tr>
<tr>
<td>base case</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>80</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>0</td>
</tr>
</tbody>
</table>

* 68% CO, 23% H\(_2\), 5% CO\(_2\) and 4% H\(_2\)O in mole fraction, 1123 K, total gas volume 199 500 Nm\(^3\)/h

The iron-blending materials (66% TFe in mass fraction) is charged from furnace top with constant flow rate of 190 t/h, the reducing gas (68% CO, 23% H\(_2\), 5% CO\(_2\) and 4% H\(_2\)O in mole fraction, 1123 K) is injected through inlets with constant volume flow rate assuring the top gas consumption per ton iron-blending materials equal to about 1 050 Nm\(^3\)/t. The other relevant formulations for phase properties and chemical reaction enthalpy have been previously published.
VDR increases, the volume fraction of the reducing gas injected through NI gradually decreases from 100 to 0% by 20% step while that through DI or PI correspondingly increases to maintain the whole gas volume constant. Other boundary conditions and relevant assumptions are given as below.

1. The stock profile is inverted ‘V shape’ with the inclination angle of 35°;
2. The average burden particle size is 15.4 mm and keeps constant as burden descending;
3. The voidage of mixture burden column is 0.358 and kept constant as burden descending;
4. The top gas pressure is fixed at 330 kPa.

In addition, three horizontal levels, namely low, middle and high levels respectively, are selected (refer to Fig. 2(a)) to demonstrate the gas velocity distributions in radial direction. The average DRI reduction degree at the bottom outlet is assumed to represent product quality in each case.

3.2. Model Validation

Before applied to predict furnace working conditions under different injection methods or top gas recycling in later section, the mathematical model is varified against practical operation data. In present work, the top gas composition (CO, CO₂ and H₂) from the numerical results of single NI or base case is compared with the counterparts (average daily data) in practical operation under about 190 t/h iron-blending burden charging flow rate and about 1050 Nm³/t top gas consumption per ton iron-blending materials, the results are shown in Fig. 3. The average CO, CO₂ and H₂ concentrations in shaft furnace top gas of 21 days are 40.95%, 33.35% and 14.10% in mole fraction respectively, while the corresponding results calculated by the mathematical model are 40.43%, 32.96% and 13.97%. The difference between the results is below 0.52%, which proves that present model is reasonable to be used for the following numerical prediction works.

3.3. Comparison among Single NI, NI+DI and NI+PI Injection Methods

The numerical results of single NI, NI+DI and NI+PI injection methods are compared in terms of gas velocity distribution, gas utilization ratio and burden reduction degree. Figure 4 demonstrates gas velocity distribution in the radial direction at the high, middle and low horizontal levels respectively. It is found that the increase of VDR in NI+DI and NI+PI methods obviously gives rises to gas velocity at the lower part of the furnace, where the reduction potential is improved by the reducing gas injected through either DI or PI. For NI+DI method, the gas flow pattern changes gradually from flat to preferential flow in the central region due to the location of DI. The gas velocity at the low level reaches as high as 3.7 m/s when VDR increases to 100%. For NI+PI method, highly increased peripheral gas flow around NI pushes the ascending gas from bottom towards the center, thus also increasing the central gas velocity at the low level by 1.7 m/s at most. Since PI is another side injection to NI, it is interesting to find that as VDR increases further,
the peripheral gas flow is gradually promoted by the reducing gas injected through PI. When VDR increases to 80%, the gas flow at the low level features almost uniform distribution in the radial direction, which is likely to improve the reduction efficiency in the high temperature zone of the shaft furnace. As for the gas distribution at both middle and high levels, NI+DI method prefers to promote the central gas flow while NI+PI one is favorable to obtain even gas distribution in increasing VDR operations, which is generally similar to the results obtained at the low level. However, under the same VDR level, the difference in gas flow distributions between NI+DI and NI+PI methods at the upper part of the furnace is much smaller than that at the lower part, which indicates that the influence of the injection method on the reduction efficiency is mainly determined by the gas distribution behaviors near the bottom of the shaft furnace.

As far as the output economical indices of the shaft furnace are concerned, the top gas utilization and DRI reduction degree for the two bi-inlet operations are predicted based on the simulation results and demonstrated in **Fig. 5**, where both CO and H₂ utilization ratios are calculated by Eq. (1). The results show the following three aspects: (1) CO utilization ratio is generally improved by adopting both bi-inlet injection methods in comparison with base case, the gas injected through PI has longer path than that through DI, which would extend the contact time between gas and solid. As a result, the utilization ratio of CO in NI+PI method is higher than that in NI+DI method by 2.6% at most when VDR is 100%. (2) With increasing VDR, H₂ utilization ratio reaches the maximum value, 40.3% at VDR=40% in NI+DI method and 41.8% at VDR=60% in NI+PI method respectively, and then falls by 4.5% and 2.1% at VDR=100% respectively, which indicates that endothermic effect of iron oxide reduction by H₂ may reduce local temperature around the inlet region, then conversely restrain the improvement on reduction rate. From these facts, H₂ injection through two inlets rather than single one with almost equal gas volume gives a positive effect on its utilization. (3) DRI reduction degrees at the bottom outlet feature a decline trend with increasing VDR in NI+DI method, the reducing gas through PI enlarges the region for the reduction from wustite to metallic iron, which would be discussed later, while DRI reduction degree at the bottom outlet decreases to 44.0% at VDR=100%. However, reduction degree level benefits from increasing VDR of the reducing gas through PI because of its closer location to DRI outlet, and reaches as high as 60.7% at VDR=80%.

In order to further clarify reduction phenomena inside the furnace for all injection methods, burden reduction degree distributions for base case, NI+DI method with VDR=20% and NI+PI method with VDR=80% are demonstrated respectively in **Fig. 6**. Compared with base case, NI+DI method improves the wustite reduction above the man-made deadman, thus expanding the region with burden reduction degree between 0.2 and 0.5. As a result, calculated distribution of burden reduction degree shows ‘W shape’. Meanwhile, it is also found that the gas through DI has much more powerful upward flow rather than downward flow through NI because of the injecting direction, resulting in low reducing agent concentration near the bottom. In another word, NI+DI method obliviously enlarges the metallic iron existing region but provides less contribution to product reduction degree level. On the contrary, burden reduction degree distribution shows a typical ‘V shape’ for NI+PI operation since both NI and PI are side-blow inlets. DRI reduction degree at the bottom is greatly improved by about 10–15% although the metallic iron existing region becomes narrow.

As a whole, distributing the reducing gas into two inlets rather than single one intensifies gas flow at the lower part of the shaft furnace, improving gas utilization ratio and product quality. Compared with DI, the lower location of PI increases the gas flow path, which greatly contributes to the improvement of DRI reduction degree level at the outlet. Besides, DRI down pipe, which is used to convey DRI to...
the melter gasifier, is easy to be installed with gas inlet equipment. In addition, under present calculation conditions, VDR=80% provides optimal DRI reduction degree for NI+PI method. Therefore, the method that 20% of the reducing gas in volume fraction is injected through NI while the rest through PI, is regarded as the best choice of bi-inlet injection for the COREX® shaft furnace.

3.4. Parameters Optimization for NI+PI Injection Method

Although NI+PI method is preferable to the shaft furnace as mentioned above, it is also of great importance to optimize parameters for PI, such as vertical height and injection velocity. As for the latter parameter, the inlet diameter, which is inversely and linearly proportional to injection velocity in two-dimensional mathematical model, is introduced to facilitate the expression. In this section, the location of PI is assumed as 1 m, 3 m and 5 m above DRI outlet with the diameter varying from 100 to 300 and 900 mm respectively. The group schemes listed in Table 3 are examined. The CO and H2 utilization ratios as well as DRI reduction degrees based on the simulation results of each scheme are collected and compared in Fig. 7.

Firstly, increasing the height of PI would inevitably shorten the gas flow path inside the furnace, thus reducing CO reduction efficiency. On the other hand, as PI approaches the bottom DRI outlet, the heat carried by the reducing gas through PI could not fully transfer upward as a result of burden descending, so the narrow high temperature region may restrain H2 utilization. Secondly, the increasing diameter of PI generally enlarges high-temperature zone around the inlet because width enlargement effect is higher than length shortening effect, which increases reduction rate leading to enhancement of DRI reduction degree level. In a word, PI should be located near bottom with large diameter aiming to improve the utilization ratio of CO in consideration of the facts that CO still plays a major role as reducing agent in present gas composition and cutting down CO2 emission from steel plant is an urgently required issue around the world.

4. Numerical Prediction and Results on Top Gas Recycling

4.1. Flow Chart of Materials Balance

According to above results, NI+PI method with 900 mm diameter of PI inlet located at the height of 1 m up from the bottom DRI outlet is examined to apply the top gas recycling technology for the COREX® shaft furnace as shown in Fig. 8. Since the temperature of the hot reducing gas, produced by coal combustion in melter gasifier, is 1 323 K in order to prevent tar condensation, the recycled gas after CO2 and H2O removal only needs to be preheated to certain low temperature level to adjust the mixture gas temperature around 1 123 K. Before injecting the mixture gas into the shaft furnace through NI and PI with the VDR equal to 80%,
the dust should be caught and recycled by cyclone. It should be stressed that the total volume of the reducing gas injected into the shaft furnace with top gas recycling is the same as that stated in above section.

The calculation flow chart and corresponding materials balance are demonstrated in Fig. 9. At the very beginning of the calculation, except for the gas composition of the hot reducing gas from melter gasifier, the variables, such as gas composition and volume fraction of the reformed gas in the mixture (written as Reformed Gas (A)) in Fig. 9(a), are assumed. After solving the conservation equations of continuity, momentum, energy and species transport in steady state by using the two-dimensional mathematical model established in section 3.1, the flow rate and composition of the reformed gas (written as Reformed Gas (C)) is determined by removing CO2 and H2O from top gas based on the calculated results. Hence, both the flow rate and composition between Reformed Gas (A) and (C) are compared and the agreement is judged. If neither the flow rate nor the composition of the reformed gas agrees with each other, Reformed Gas (A) is updated to (U) by substituting the calculated results of Reformed Gas (C). This circulation is continued until convergence is obtained and the optimal results for the top gas recycling are represented in Fig. 9(b). Above mentioned simulation provides following three results: (1) The required fresh hot reducing gas from melter gasifier reduces by 51%, in another word, it is likely to reduce CO2 emission from the whole process by 540.6 Nm3/tHM under present simulation conditions. (2) The recycled gas only needs to be preheated to 927 K to control the mixture reducing gas temperature to 1123 K by mixing with the hot reducing gas featuring 1323 K. (3) The utilization ratio of CO or H2 increases by 6.0% or 8.3% to 46.9% or 46.5% in comparison with the counterpart in base case.

4.2. Furnace Internal State

In order to clarify the difference in the furnace internal state between normal operation (written as Base Case) and the operation with top gas recycling (written as Top Gas Recycling), the contours of CO and H2 mass fractions, solid temperature and reduction degree are depicted respectively in Fig. 10.

Figure 10(a) shows the mass fraction distributions of CO in the gas phase for base case and top gas recycling. Firstly, since the fresh reducing gas produced by melter gasifier also gets rid of nitrogen, the overall improvement of CO partial pressure inside the furnace is not as remarkable as that inside BF applying top gas recycling.19) Secondly, it is worthy to note that the CO concentration at the bottom in top gas recycling case is much higher than that in base case, especially in the region around the bi-inlet, which greatly contributes to the improvement on DRI reduction degree level. Thirdly, both cases show little difference in CO concentration at the upper part of the shaft furnace, because the relatively low temperature directly restrains the reduction degree.
kinetics. The mass fraction distributions of $\text{H}_2$ for both cases are also compared in Fig. 10(b). The general difference between base case and top gas recycling case is similar to that of CO mass fraction as mentioned above, but the region for $\text{H}_2$ reduction is narrower, which indicates that CO still plays a major role in iron ore reduction under present shaft furnace operation conditions. Fig. 10(c) shows the solid temperature distributions for both cases. It is obviously to find that the vertical strip region with the solid temperature above 1023 K in base case has been divided into two regions, located near NI and PI respectively in top gas recycling case. Meanwhile, although the overall high temperature field moves upwards, the continuously charging materials from top reduce such influence on the solid temperature at the upper part of the shaft furnace. As far as burden reduction degree distribution is concerned, it has been greatly improved near the bottom DRI outlet as shown in Fig. 10(d), which is in accordance with above results. The area of metallic iron existed zone is narrower while the wustite reduction near the bottom is greatly improved, thus increasing the average DRI reduction degree by about 12.4%.

5. Further Discussion

Some viewpoints are worth being discussed as to the application of top gas recycling technology to COREX® shaft furnace. For side-blow injection pressure, under the premise of fixing top gas equal to 330 kPa, the value at NI is calculated as 374 kPa in base case. As VDR increases, the reducing gas through NI is replaced partially by PI, thus decreasing the injection pressure at NI by about 5 kPa but dramatically increasing the pressure at PI (1 m Height with 300 mm diameter) by about 43 kPa at most as a result of the increasing gas path. Although present work reveals that increasing the diameter of PI from 300 to 900 mm helps to reduce its pressure by about 11 kPa, improving burden column permeability and decreasing gas velocity are the crucial technologies to ease the injection pressure increase at PI.

Since the whole COREX® process consist of not only shaft furnace but melter gasifier, the work conditions of the latter metallurgical furnace should also be further taken into consideration. For example, the thermal conditions inside gasifier need to supply enough energy for smelting reduction as well as heat transfer between gas and solid or liquid phases by combusting coal with oxygen injected at ambient temperature. Meanwhile, the reduction degree of DRI produced by shaft furnace also makes direct influence on carbon consumption for direct reduction in melter gasifier. As a whole, although the application of top gas recycling technology to COREX® shaft furnace has a potential to save energy consumption in melter gasifier, the evaluation of the actual energy balance of the updated process, including the energy consumption for CO$_2$ and H$_2$O removal, reformed gas preheating and export gas utilization, remains as an important subject for future work.

6. Conclusions

The top gas recycling technology is regarded as one of the highest potential methods to reduce fuel consumption, thus cutting down greenhouse gas emission from BF. Due to nitrogen free characteristic, it is reasonable to adopt the technology to make full use of the export gas featuring comparatively strong reducing potential from COREX® shaft furnace top. A two-dimensional mathematical model in steady state, considering mass, momentum and energy transfer between gas and solid phases as well as the chemical reactions, is employed to investigate the influences of three kinds of injection method, namely single NI, NI+DI and NI+PI, on the shaft furnace performance numerically. NI+DI method promotes central gas flow inside the furnace, thus extending the iron oxides reduction region upward, but the reduction efficiency in the inactive zone located near the bottom is only improved slightly. On the other hand, NI+PI method not only increases top CO and $\text{H}_2$ utilization ratio to as high as 46.3% and 41.8% respectively but greatly improves DRI reduction degree. Meanwhile, PI location near the bottom with large diameter extends space and time for the contact between reducing gas and burden solid which makes further contribution to reduction efficiency improvement. Top gas recycling by NI+PI method with VDR equal to 80% is also optimized, the fresh reducing gas required for the shaft furnace operation is reduced by half while the DRI reduction degree is increased by 12.4% in comparison with base case. Therefore, under present simulation conditions, the top gas recycling technology applied to COREX® shaft furnace is promising to improve reduction efficiency as well as cut down CO$_2$ emission by about 540 Nm$^3$/tHM.

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Nomenclature

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<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$d_c$</td>
<td>Solid particle diameter (m)</td>
</tr>
<tr>
<td>$g$</td>
<td>Gravitational acceleration (m/s$^2$)</td>
</tr>
<tr>
<td>$H^i$</td>
<td>Enthalpy of reaction $i$ at temperature $T$ (J/kg)</td>
</tr>
<tr>
<td>$K_n$</td>
<td>Equilibrium constant of chemical reaction $n$ (–)</td>
</tr>
<tr>
<td>$\rho_p$</td>
<td>Thermal conductivity of gas phase (W/m·K)</td>
</tr>
<tr>
<td>$M_i$</td>
<td>Molecular weight of species $i$ (kg/kmol)</td>
</tr>
<tr>
<td>$m_{sc}$</td>
<td>Mass rate of species $i$ in the gas inflow/outflow $j$ (kg/s)</td>
</tr>
<tr>
<td>$P_i$</td>
<td>Partial pressure of species $i$ (Pa)</td>
</tr>
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<td>$R_n$</td>
<td>Rate of chemical reaction $n$ (kmol/m$^3$·s)</td>
</tr>
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<td>Source term for variable $\phi$ in Eq. (2)</td>
</tr>
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<td>$T_p$</td>
<td>Temperature of phase $p$ (K)</td>
</tr>
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<td>$\hat{v}_p$</td>
<td>Physical velocity vector of phase $p$ (m/s)</td>
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<tr>
<td>$W$</td>
<td>Variable explained in Ref. 33)</td>
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Greek Symbols

<table>
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<td>$\alpha_{sc}$</td>
<td>Variable explained in Ref. 33)</td>
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<tr>
<td>$\alpha_{i,p}$</td>
<td>Mass fraction of species $i$ in phase $p$ (–)</td>
</tr>
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<td>$\varepsilon_i$</td>
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</tr>
<tr>
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</tr>
<tr>
<td>$\phi$</td>
<td>General dependent variable in Eq. (2)</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>Solid particle shape factor (–)</td>
</tr>
<tr>
<td>$\Gamma\phi$</td>
<td>Diffusion coefficient for variable $\phi$ in Eq. (2)</td>
</tr>
<tr>
<td>$\mu_i$</td>
<td>Viscosity of species $i$ (kg/m·s)</td>
</tr>
</tbody>
</table>

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η_{CO}: Utilization ratio of CO (–)

Subscripts
- g: Gas
- s: Solid

Abbreviations
- NI: Normal Inlet
- PI: (down) Pipe Inlet
- DI: Deadman Inlet
- VDR: Volume Distribution Ratio

REFERENCES
27) G. Q. Xu: Shanghai Met., 27 (2005), 47.