Evolution of Blast Furnace Process toward Reductant Flexibility and Carbon Dioxide Mitigation in Steel Works

Tatsuro ARIYAMA1,* Michitaka SATO2, Taihei NOUCHI3 and Koichi TAKAHASHI3)

1) Professor Emeritus, Tohoku University, 1-1, Katahira 2, Aoba-ku, Sendai, 980-8577 Japan.
2) Steel Research Laboratory, JFE Steel Corporation, 1, Kokan-cho, Fukuyama, 721-8510 Japan.
3) Steel Research Laboratory, JFE Steel Corporation, 1, Kawasaki-cho, Chuo-ku, Chiba, 260-0835 Japan.

(Received on April 8, 2016; accepted on June 21, 2016; J-STAGE Advance published date: August 25, 2016)

Blast furnace has been regarded as a highly optimized process as a result of various technological improvements over its long history. However, from the viewpoints of resources, energy and global warming, continuing evolution toward reductant flexibility and CO2 mitigation is desired. This review focuses on the progressive design of an ambitious blast furnace for the future.

First, the history of techniques for reducing coke rate and reducing agent in the blast furnace are reviewed. Pulverized coal injection is currently common; however a more innovative process is desired in order to address the global warming issue. The low temperature blast furnace based on charging of high reactivity coke is a realistic process. The combination of the oxygen blast furnace with top gas recycling is also attractive. Although the top gas recycling process based on the oxygen blast furnace is very effective for reducing CO2 emissions, a total evaluation considering the role of the blast furnace to keep the energy self-sufficiency in the integrated steel works is necessary. The oxygen blast furnace enables injection of a large amount of natural gas, and optimized injection of natural gas and pulverized coal makes it possible to mitigate CO2 emissions while maintaining the energy supply to downstream processes. Moreover, owing to the high productivity of the oxygen blast furnace, the blast furnace profile can be downsized. The characteristics of several processes are quantitatively examined, and the concept of the advanced oxygen blast furnace as a next-generation process toward carbon dioxide mitigation is discussed.

KEY WORDS: ironmaking process; blast furnace; top gas recycling; high reactivity coke; oxygen blast furnace; shaft gas injection; CO2 mitigation; global warming.

1. Introduction

Although it is possible to produce steel by various routes, as exemplified by the blast furnace, scrap melting and direct reduction with the electric arc furnace (EAF), at present, the blast furnace accounts for approximately 70% of world steel production. The current blast furnace can be regarded as a main process which is appropriate for mass production of various steel products and production of high grade steels. On the other hand, since the blast furnace depends heavily on coal as the main reductant and energy source, blast furnace operation is closely related to the issues of resources, energy and the environment, and the price of coal and the general energy situation have a large influence on the cost of steel production. To ensure stable blast furnace operation, a certain ratio of relatively expensive coking coal, which is suitable for producing high strength coke, is required. For this reason, efforts to decrease the coke rate have been an ongoing technological subject for many years. Recently, global warming has also been recognized as an urgent issue for the steel industry. In addition to conventional carbon reduction and energy saving techniques, many studies on novel technologies for reducing CO2 emissions from the steel works are being carried out from the mid- and long-term viewpoints.1–5) Although the evolution of the blast furnace with the aim of realizing low carbon in the steel works has attracted considerable attention from the viewpoint of reducing CO2 emissions, a more proactive fundamental review of the ironmaking process is needed. From these various viewpoints, technology development to reduce carbon consumption in the blast furnace is considered to be a priority issue for the steel works.

Historically, in order to reduce the coke rate, combined blast operation consisting of oil injection and oxygen enrichment was applied first in Europe, and technologies of this type were then adopted on the global scale in the 1960s.6) Subsequently, pulverized coal injection (PCI) was substituted for oil injection following a period of all-coke operation. In parallel with the development of these combined blast furnace operation, provisional research on injection of reducing gas into the blast furnace shaft was also carried out.7–11) In these processes, hot reducing gas is produced by partial oxidation and reforming of oil, natural gas or coke...
oven gas (COG), and is then injected into the lower shaft of the blast furnace in order to drastically decrease the coke rate through intensified gas reduction. Although these technologies were not commercialized for economic reasons, they nevertheless provided many significant results, later leading to the top gas recycling and oxygen blast furnace. More recently, smelting reduction processes characterized by direct use of iron ore and non-coking coal coal have attracted special attention. Several processes such as the Direct Iron Ore Smelting Reduction Process (DIOS) have been developed at the pilot plant scale. Various processes involving a combination of a pre-reduction furnace and a smelting furnace have been proposed, among which the COREX and FINEX processes were actually commercialized. The smelting reduction process seems to be ambitious; however, replacement of the blast furnace by the smelting reduction process will take time from the viewpoints of availability and reliability.

Since the 1980s, the oxygen blast furnace has been developed to enable injection of a large amount of pulverized coal in order to replace coke with coal. Many studies have been carried out on the development of the oxygen blast furnace with shaft gas injection. The oxygen blast furnace is characterized by a nitrogen-free condition which results in improvement of the reduction rate and productivity. The oxygen blast furnace also has various technological advantages from the viewpoint of CO₂ mitigation. The shaft gas injection in this process is similar to the concept of hot reducing gas injection described above. These processes indicate new aspects of innovation in the blast furnace process and suggest the basic concept for a next-generation blast furnace. Considering the current situation, greater importance should be placed on the energy self-sufficiency of the steel works when pursuing the diversification and flexibility of reducing agents, and on mitigation of CO₂ emissions by innovative ironmaking processes.

This paper reviews the desirable future evolution of the blast furnace toward optimization and diversification of reducing agent utilization, energy flexibility and CO₂ mitigation, considering past technology developments related to the blast furnace. In the later half, a perspective on an ambitious blast furnace process to meet future requirements is described on the basis of recent studies.

2. Historical Transition and Review of Blast Furnace for Low Carbon

2.1. Progress of Blast Furnace

The transition of the blast furnace is shown in Fig. 1. As mentioned above, in the 1960s, combined blast operation utilizing a combination of oil injection and oxygen enrichment contributed to a reduction in the coke rate. After the Oil Crisis, PCI became a common practice following a period of all-coke operation. Although some problems of combustibility and permeability were experienced at the time, various technical improvements were made, and PCI became a basic technology for the blast furnace in every country. Around the 1970s, research projects on injection of hot reducing gas into the blast furnace shaft were carried out with the aim of drastically reducing the coke rate. The reducing gas for this process was produced by reforming COG or oil. The effect of reducing gas injection was verified with an experimental blast furnace and in test operation with a commercial blast furnace.

After the 1980s, the oxygen blast furnace attracted special attention from the viewpoint of massive coal injection. Conventional PCI surely makes it possible to replace coke with coal; however, the replacement ratio is restricted by the limited oxygen concentration in the hot blast. Full oxygen injection drastically improves the combustibility of pulverized coal, and a PCI ratio of 320 kg/tm was verified with an experimental blast furnace. Moreover, the nitrogen-free condition in the furnace contributes to acceleration of the reduction rate and increased productivity. These characteristics of the oxygen blast furnace lead to the concept of a new blast furnace for CO₂ mitigation. There are several types of oxygen blast furnaces which employ a combination of preheated gas injection and injection of reducing gas after CO₂ removal. In the JFE Steel oxygen blast furnace, preheated gas injection into the upper shaft was applied to compensate for the high heat flow ratio derived from the nitrogen-free furnace condition with the aim of simplifying the total process.

Control of the reduction equilibrium has been proposed to decrease the reducing agent in the current blast furnace. Lowering the thermal reserve zone temperature, which is related to the reduction equilibrium, is effective for increasing the gas utilization ratio, thereby making it possible to decrease reducing agent. Control of the thermal reserve zone temperature is possible by charging high reactivity coke. This process is represented as the “Low temperature BF” in Fig. 1. Ferro-coke containing metallic iron is considered to be a typical high reactivity coke. Here, metallic iron functions as a catalyst to promote the solution loss reaction in the thermal reserve zone of the blast furnace. This process is easily applicable to the current blast furnace.

Since the end of the 20th century, global warming has been recognized as a critical issue, and as a result, low carbon processes have been pursued in the steel industry. The ironmaking process has a particularly large influence on CO₂ emissions due to its large carbon consumption. Therefore, the applicability of CO₂ sequestration to the ironmaking process has been examined. From this viewpoint, a top gas
recycling process which includes CO₂ sequestration prior to reuse of the top gas was proposed to drastically decrease CO₂ emissions. After CO₂ removal, the top gas is injected into the lower shaft or through the tuyeres to replace direct reduction by carbon with gas reduction. The NBF (New Blast Furnace) in the ULCOS (Ultra Low CO₂ Steelmaking) project is a representative process utilizing top gas recycling. Following the development of that process, similar processes have also been actively studied. Top gas recycling is considered to represent a further evolution of the previous reducing gas injection process.

Recently, the concept of intensified natural gas injection in a downsized blast furnace utilizing the characteristics of the oxygen blast furnace such as high productivity has been proposed; this type of blast furnace is classified as an advanced oxygen blast furnace. This concept enables a reduction in the carbon input to the ironmaking process, energy saving and energy supply to the downstream processes. Owing to the high productivity of the oxygen blast furnace, the furnace profile can be reduced, and this makes it possible to use low grade burden materials. This approach is advantageous for the integrated steel works, considering its compatibility with both the energy balance in the steel works and CO₂ mitigation.

Figure 2 shows the coke rate range predicted in each process. In PCI processes, the coke rate can normally be reduced to approximately 300 kg/thm. The lower limit is determined by the combustibility of pulverized coal, which is relating to the replacement ratio, and permeability in the blast furnace. Here, it should be noted that these conditions are influenced by the type of coal used for injection and the burden quality. As described above, the coke rate can be drastically reduced by injection of a reducing gas. Direct reduction in the blast furnace, which is related to the coke rate, can be replaced by indirect reduction by injecting a reducing gas into the lower shaft. According to a theoretical analysis of the mass and heat balance in a blast furnace, the lower limit of the coke rate is estimated to be 220 kg/t, and under this condition, the direct reduction ratio approaches nearly zero. A theoretical estimation based on a mathematical simulation showed that the coke rate approaches a similar lower limit in an oxygen blast furnace with massive coal injection. According to Ohno et al., the minimum coke rate is estimated to be 230 kg/thm in the commercial oxygen blast furnace. In the oxygen blast furnace with top gas recycling, the coke rate will be slightly lower than that in the previous oxygen blast furnace due to more intense indirect reduction. It is estimated that the advanced oxygen blast furnace with optimized hydrogenous injectants as described later will have a coke rate of around 200 kg/thm. To decrease CO₂ emissions, special emphasis should be placed on the selection of injectants appropriate for achieving low carbon based on the cold oxygen injection as shown in Fig. 2.

2.2. Relative Position of Blast Furnace Compared with Other Processes

Figure 3 shows the relationship between the iron ore resources and reductants in various ironmaking processes. As is well known, the current blast furnace mainly depends on agglomerates such as sinter or pellets and lump ore as iron resources, and the main reductants are derived from coal. Figure 3 shows the production capacity scale by concentric circles. The annual production scale of one blast furnace reaches approximately 4 million tons. Direct reduction processes based on natural gas, such as MIDREX and TENOVA HYL, which are located in the lower right region, are certain to be adopted widely throughout the world owing to the availability of shale gas. The scale of a plant which is now under construction in the United States will reportedly be around 2.0–2.5 million tons/year. Various other processes are positioned in the upper left region of Fig. 3, where iron ore fines and coal are used. Smelting reduction processes (Hlsarna, DIOS, FINEX) and rotary hearth processes (FASTMET, ITmk3) can be cited as examples of this direction in ironmaking. COREX is a kind of smelting reduction process, it is dependent on agglomerates. These are considered to be promising processes because direct use of non-coking coal is possible, however their production capacity is smaller than that of the blast furnace. Only the capacity of FINEX is gradually being enlarged to 2.0 million tons/year. Looking at the relative positions of the various processes, the blast furnace excels in production capacity and reliability. However, the operation of current large blast furnaces with inner volumes exceeding 5 000 m³ requires high quality burden and is dependent on coal as a reductant and energy source. Considering the issue of global
warming, use of hydrogen-rich reductants such as natural gas should be actively pursued as a direction for the future blast furnace. Flexibility of burden quality and reduction of carbon dependency are also considered to be present subjects for the evolution of the blast furnace.

2.3. Approaches to Lowering Reducing Agent and Coke Rate

$\text{CO}_2$ emissions from the steel works are closely related to reducing agent consumption in the blast furnace. Figure 4 shows the reduction mechanism in the blast furnace, which is related to reducing agent. Figure 4 also shows the essential approaches to achieving low carbon based on the reduction mechanism. These approaches can be visually represented in the Rist diagram, as shown in Fig. 5.

Control of reduction equilibrium by high reactivity coke can be considered as a first approach. In this case, the W point in the Rist diagram in Fig. 5 shifts to the right due to lowering of the thermal reserve zone temperature. Second, reducing gas injection is an effective path to intensify indirect gas reduction. As described above, previously, hot reducing gas is produced by reforming oil, COG or natural gas, and hot reducing gas is injected to the lower shaft. In this case, point B in Fig. 5, corresponding to the direct reduction ratio, shifts downward as a result of an increase in the indirect reduction ratio by gas reduction. The top gas recycling based on cold oxygen injection can more effectively intensify the indirect reduction through shaft gas injection. Although reducing agent apparently increases on a molar basis, the coke rate can be drastically reduced. These tendencies can be seen graphically in Fig. 5. The selection of hot blast or cold oxygen injection has an influence on the specific oxygen gas volume. In the case of cold oxygen injection, the specific oxygen gas volume increases because the sensible heat of the hot blast cannot be utilized. Accordingly, point E in Fig. 5 moves downward when cold oxygen injection is adopted. Conversely, point E shifts upward in the case of reducing gas injection utilizing hot blast. The points E’ and E” in Fig. 5 correspond to the respective cases. In all cases, point B, corresponding to the direct reduction ratio, moves downward from B to B’ or B”. If top gas recycling with $\text{CO}_2$ sequestration is applied, top gas without $\text{CO}_2$ provides the driving force for the downward movement of point B, which implies a decrease in the coke rate.

Summarizing the above approaches to achieving low carbon, full oxygen injection is more advantageous because various injectants such as pulverized coal or natural gas can be effectively used up to the limit of combustibility in the raceway. Moreover, the nitrogen-free condition accelerates the reduction rate of iron oxide and thereby improves productivity. Based on these considerations, the desirable process for low carbon is obvious. Then, the energy balance has an essential relationship with the energy self-sufficiency of the integrated steel works as a whole. The energy balance in the case of top gas recycling will be discussed in a later chapter.

3. Decrease in Reducing Agent by Control of Reduction Equilibrium

As an actual use of the current blast furnace facility, improvement of gas utilization through lowering the thermal reserve zone temperature by charging high reactivity coke can be mentioned as a realistic path to low carbon. This approach means control of the reduction equilibrium of FeO–Fe. High reactivity coke shifts the thermal reserve zone to a lower temperature region. In Fig. 5, the gradient of the operating line equivalent to the reducing agent can be decreased by the shift from point W to W’ on the assumption that shaft efficiency is kept constant. Various studies on the charge of high reactivity coke have been performed, and it is considered that the catalyst addition of alkaline earth metals such as Ca or transition metals such as Fe is effective for accelerating coke reactivity.26–33) The high reactivity coke initiates the reaction with $\text{CO}_2$ at a lower temperature, which lowers the thermal reserve zone temperature. This implies a shift of the FeO–Fe reduction equilibrium gas composition to a higher $\text{CO}_2/(\text{CO}+\text{CO}_2)$ composition, leading to lower reducing agent.

Nomura et al. proposed the idea of Ca- or Fe-coated coke for post addition of the catalyst and confirmed the high reactivity of catalyst-coated coke in which the catalyst is concentrated at the surface.30) Subsequently, they studied formed iron coke and the reaction behavior of a mixture of iron coke and conventional coke. Their research confirmed that iron coke reacts near the thermal reserve zone temperature, whereas conventional coke barely reacts and thus...
is protected. In other words, selective reaction of iron coke in a lower temperature region can be expected. A long-term production test of Ca-rich high reactivity coke was performed at a commercial coke oven at Muroran Works, and the high reactivity coke was charged to Muroran No. 2 BF. The operational results showed that reducing agent decreased by 10 kg/thm when the blending ratio of Ca-rich coal was increased.

Yamamoto et al. proposed the concept of a ferro-coke material named Carbon Iron Composite (CIC), which contains metallic iron as a catalyst. First, coal and iron ore fines are agglomerated in a briquetting process, and CIC is produced from the agglomerates through carbonization in a vertical-type coke oven like that used in the production of formed coke. The total concept of CIC charging in the blast furnace is shown in Fig. 6, which presents a graphic illustration of the change in the temperature profile in the blast furnace and the operation line in the Rist diagram. The W point moves toward the lower right due to the effect of charging of the metallic iron and lowering of the thermal reserve zone temperature. It is considered that metallic iron acts as a catalyst for active gasification of the coke through the redox reaction, as shown in Fig. 6. In order to effectively utilize the high reactivity of CIC, mixed charging of CIC in the ore layer has also been proposed, as shown in Fig. 7. This approach is based on a functional differentiation between conventional coke, which maintains furnace permeability, and high reactivity coke, which is used to control the reduction equilibrium. Then, the use of iron ore with high reducibility is desired to maintain reduction rate even in the lower temperature condition as described in the previous studies.

Figure 8 shows the concept of the total ironmaking process including a CIC process. The CIC process is installed in parallel with conventional coke ovens. Here, the conventional coke ovens provide coke, which serves as a spacer to maintain the permeability of the blast furnace, and the CIC is used for gasification. According to fundamental research, it is estimated that the initial temperature of the CO$_2$ reaction of coke changes from 1050°C to 900°C, and reducing agent is reduced by 10%. The total effect of CIC charging is shown in Fig. 6, where 101 kg/thm of CIC briquettes containing 27.9% iron ore fines are charged. As shown in Fig. 8, although additional carbon consumption for CIC process is required, decrease in carbon consumption in conventional coke oven and sintering machine owing to metallic charge effect of CIC and reduction of reducing agent in blast furnace are expected. Then, the total decrease in carbon consumption is estimated to be 6.1% compared with the conventional ironmaking process. Moreover the vertical-type oven used for CIC has a sealed structure which is favorable for environmental protection. Since chamotte brick is used in the vertical-type coke oven in place of silica brick in this process, the coke oven wall is less liable to form martensitic fayalite (2FeO·SiO$_2$). This process may possibly provide the basic low carbon ironmaking process when using the current blast furnace.

4. Reducing Gas Injection and Oxygen Blast Furnace

4.1. Early Stage of Development of Reducing Gas Injection Process

In a blast furnace, it is well known that reducing gas is mainly produced by combustion of coke in the raceway and direct reduction in the lower part of the blast furnace. If generation of reducing gas by combustion of coke is replaced by injection of reducing gas, the coke rate can be drastically reduced. This concept was introduced in Figs. 4 and 5. In the early stage of development of the reducing gas injection process, combination with a gas reforming process utilizing natural gas, oil or COG was proposed. In Japan, the FTG
and NKG processes were actively developed as gas reforming processes. In FTG, reducing gas is produced by partial oxidation of heavy oil. A short trial at a commercial blast furnace with an inner volume of 1,691 m$^3$ equipped with four auxiliary tuyeres in the lower shaft was carried out, and the effect of reducing gas injection was verified. The configuration of the NKG process is shown in Fig. 9. This process consists of a pair of BFG heaters and COG reformers, and operation is periodically repeated through heating and reforming periods. The reducing gas is produced by reforming the CH$_4$ in COG with the CO$_2$ in BFG, and is then supplied to the lower shaft of the blast furnace. Since CO$_2$ rich BFG is favorable for the reforming process, selective take-out of the peripheral gas at the blast furnace throat with high CO$_2$ concentration has been proposed to promote the reforming reaction effectively. The NKG process was verified with a 4.0 m$^3$ experimental blast furnace.

Figure 10 shows the effect of reducing gas injection on the change in the coke rate by a simulation model. As the reducing gas volume increases, the direct reduction ratio decreases and as a result, the coke rate decreases remarkably. Figure 10 indicates the advantageous effect of the above-mentioned selective take-out of peripheral gas. A feasibility study on the energy balance in the integrated steel works and an analysis of the gas penetration of the injected gas were also carried out. According to the feasibility study, the possibility of the reducing gas injection process utilizing COG depends on the balance of the prices of coke and purchased energy. This implies that the self-sufficiency of the energy balance in the integrated steel works is a high priority.

4.2. Development of Oxygen Blast Furnace and Its Characteristics

Various types of oxygen blast furnaces have been proposed, as shown in Fig. 11, including theoretical studies carried out around the 1980s. There are various processes regarding the application of shaft gas injection or preheated gas injection. Shaft gas injection processes apply a CO$_2$ separation system in order to reproduce the reducing ability of top gas. Although these processes result in CO$_2$ mitigation, the energy balance is a matter of concern, as the blast furnace is an important source of energy for downstream processes in an integrated steel works. As an example, Fig. 12 shows a comparison of the oxygen blast furnace with preheated gas injection and the conventional blast furnace. This process was actually verified with an experimental blast furnace. In any case, the nitrogen-free condition resulting from oxygen injection promotes indirect reduction, which is similar to the concept of reducing gas injection shown in Fig. 5.

The oxygen blast furnace has several features. First, the oxygen blast furnace can be operated with higher productivity because the concentration of reducing gases such as CO and H$_2$ increases and the specific bosh gas volume decreases under a nitrogen-free condition. The productivity of the
The direct reduction ratio in the oxygen blast furnace decreases due to the intensified gas reduction under the nitrogen-free condition, leading to a reduction of the solution loss reaction. This is effective for suppressing coke degradation, which is important from the viewpoint of permeability. The total in-furnace phenomena related to high productivity are shown in Fig. 13.

Owing to the high combustion capability in the raceway of the oxygen blast furnace, a large quantity of injectants can be blown into the tuyeres and diversified injectants can be used. The maximum pulverized coal rate of 320 kg/t was achieved with the above-mentioned experimental blast furnace.\(^{20,23}\) At present, in addition to pulverized coal, intensified natural gas injection is considered to be suitable for the oxygen blast furnace since the decomposition heat of natural gas can be utilized to control the flame temperature. Use of hydrogen-rich injectants such as natural gas also helps to decrease CO\(_2\) emissions from the steel works. Moreover, the oxygen blast furnace can produce top gas with a higher calorific value than the conventional blast furnace. In the examples shown in Fig. 12, the calorific values of the BFG produced by the conventional blast furnace and the oxygen blast furnace are 3.0 MJ/Nm\(^3\) and 6.4 MJ/Nm\(^3\), respectively. High calorific top gas can be utilized effectively in other processes such as the power plant or as a chemical resource.

On the other hand, the oxygen blast furnace also has inherent issues. Due to the decreased bosh gas volume, preheating of the burden in the shaft region tends to be insufficient in comparison with the conventional blast furnace. To compensate for the insufficient heat supply in the shaft, it is necessary to inject preheated gas in the upper shaft. Otherwise, sufficient reducing gas from the top gas must be injected into the tuyeres or an auxiliary tuyere in a well-balanced state in the heat supply.

5. Assessment of Oxygen Blast Furnace with Reducing Gas Injection

5.1. Subsequent Subjects of Shaft Gas Injection

Reducing gas injection has several advantages. However, the reducing gas injected into the shaft must act effectively in the reduction of iron ore. Gas penetration in the furnace cross section (radial direction) is related to the effectiveness of reducing gas injection. Mathematical simulations of gas penetration based on the discrete element method (DEM) and computational fluid dynamics (CFD) were carried by Natsui \textit{et al.}\(^{47,48}\) Figure 14 shows the gas velocity vectors calculated by a three-dimensional mathematical model. In Fig. 14, three types of blast furnaces with different inner volumes are presented as examples. The gas penetration area is shown in red. It was found that reducing gas penetration is limited to the peripheral region near the furnace wall. In particular, this tendency is noticeable in large blast furnaces. The region influenced by shaft gas injection is restricted to the vicinity of the auxiliary tuyeres. The gas flow and penetration of injected shaft gas can be schematically explained by Fig. 15. At the injection level of the shaft gas, the isobaric plane is curved in the vicinity of the injection point. The upward gas flow is forced to the center of the furnace by the injected gas. However, the isobar plane becomes flat in the region above the injection level. This means that the gas velocity distribution is substantially uniform across the furnace radius. Accordingly, as shown in Fig. 15, it is estimated that the penetration area of the injected gas is proportional to the relative gas volume of the injected gas. Although this study does not include the diffusion effect, the above results agree with the previous experimental results reported by Nishio \textit{et al.},\(^{11}\) who considered the diffusion effect of injected gas by a three-dimensional cold model and theoretical calculations. Recently, the mathematical simulation of the shaft gas injection with the total model including heat and mass transfer was carried out by Zhang \textit{et al.}\(^{49,50}\)
where the uneven gas concentration profile across the radius direction by the shaft gas injection was reported. These results are similar to the previous papers. Therefore, in order to promote shaft gas injection effectively, it is necessary to take into account the blast furnace profile, the injection point and the injection gas volume, as these factors influence the penetration effect of the injected gas.

Additionally, in the reducing gas heating process for shaft gas injection, carbon deposition possibly occurs. Carbon deposition causes the problem of metal dusting on the equipment surface. Ferrous dusts included in the reducing gas accelerates carbon deposition as catalysts. Metal dusting is a type of corrosion resulting from a carbonaceous atmosphere and is a leading cause of serious damage in the high temperature components of reducing gas plants. In view of similar phenomena in chemical processes such as synthetic gas production plants, carbon deposition is considered to be a crucial issue for commercializing reducing gas injection system such as top gas recycling.

5.2. Unit Model Studies of Mass and Energy Balance

In order to estimate the changes in the ironmaking process accompanying the introduction of the oxygen blast furnace, a mass and heat balance model is required. In particular, estimation of energy and carbon consumption is extremely important for a quantitative assessment of the advantages of the oxygen blast furnace. Moreover, the performance of the integrated steel works as a whole must also be examined. These analyses were recently carried out by the following authors.

Figure 16 shows the top gas recycling process model developed by Jin et al., including a one-dimensional model of heat transfer and the reactions in the stack and bosh zone of the blast furnace, an equilibrium model for combustion at the main tuyere level and a mass and energy balance model for the separation and preheating of the top gas. They focused on the carbon consumption in the blast furnace region and considered the energy required for blast power, oxygen production and CO₂ separation in the estimation of CO₂ emissions. A typical example is shown in Fig. 17. The carbon input to the top gas recycling blast furnace is about 30% less than that in the conventional blast furnace. Net CO₂ emissions can be reduced by 38.6% in Case b) of Fig. 17 compared with the conventional blast furnace in Case a). In this case, 100% of the BFG is recycled to the reducing gas injection system through VPSA (Vacuum Pressure Swing Absorption Process).

Figure 18 shows one converged solution based on the mass and heat balance model proposed by Sahu et al. This solution is obtained by iteration procedure on the mass and heat balance model, on the condition that gas utilization values such as ηCO and ηH₂ are given. Many calculations were done until a converged solution was reached. The relationship of the recycling gas with the energy available for downstream processes and the CO₂ available for sequestration is shown in Fig. 19. As is shown in Fig. 19, although intensified top gas recycling enables effective CO₂ sequestration, there is a substantial reduction in available downstream energy. Since it is necessary to forecast the additional energy supply required to meet the energy demand in the integrated steel works, as well as the associated CO₂ emissions from the production of that energy, re-estimation of the net carbon emissions of an integrated steel works based on the top gas recycling blast furnace is required.

5.3. Total Model of Mass and Energy Balance in Ironmaking Process

5.3.1. Structure of Total Model

The authors presented a total model of the mass and energy balance model proposed by Jin et al. and Sahu et al. This model includes a one-dimensional model of heat transfer and the reactions in the stack and bosh zone of the blast furnace, an equilibrium model for combustion at the main tuyere level, and a mass and energy balance model for the separation and preheating of the top gas. They focused on the carbon consumption in the blast furnace region and considered the energy required for blast power, oxygen production and CO₂ separation in the estimation of CO₂ emissions. A typical example is shown in Fig. 17. The carbon input to the top gas recycling blast furnace is about 30% less than that in the conventional blast furnace. Net CO₂ emissions can be reduced by 38.6% in Case b) of Fig. 17 compared with the conventional blast furnace in Case a).

Fig. 16. Model structure of top gas recycling based on oxygen blast furnace process. 41)

Fig. 17. Material flow in conventional blast furnace and oxygen blast furnace with top gas recycling. 41)

Fig. 18. Mass flow diagram of one converged solution of high blast enrichment. 52)
energy balance, as shown in Fig. 20. The model elements consist of the sintering machine, coke oven and blast furnace and also include the power plant, hot stoves and oxygen plant. In addition to these facilities, this model includes various equipment such as the blower of the blast furnace and the facilities in downstream processes. The model of the blast furnace is based on a Rist diagram. Since the original Rist diagram does not include preheated gas injection and shaft gas injection, this Rist diagram was partly modified.

The mass and energy balances in the integrated steel works for each case were calculated considering the facilities and equipment shown in Fig. 20. Excess energy (E) is defined as generated energy (BFG + COG) minus energy consumed in the ironmaking process (fuel for the coke oven, sintering machine, hot stove and power plant). The objects of these calculations are shown in Fig. 21. Figure 21(a) is an oxygen blast furnace with top gas recycling with and without a CO2 capture process, and (b) is the advanced oxygen blast furnace described later, meaning a revised oxygen blast furnace process which is suitable for diversified energy sources. In that process, a hydrogen-rich injectant such as natural gas is introduced together with pulverized coal through the tuyeres.

The calculation conditions are shown in Table 1. Case O-00 is a reference condition characterized by massive coal injection, which is the previous concept of the oxygen blast furnace that pursued the economic advantage of gas generation in spite of high reducing agent consumption. Cases O-01 to O-04 are top gas recycling processes with CO2 capture. It is assumed that the CO2 included in the top gas is captured with 100% efficiency prior to top gas injection into the shaft and tuyeres, and after CO2 capture, some part of the top gas, which is heated to 1 000°C, is injected into the shaft. The remainder is introduced into the tuyeres as tuyere gas injection so that the flame temperature in the raceway is appropriately controlled. Basically, in the case of a higher injection rate of tuyere gas, the PCI rate is decreased in order to maintain the proper flame temperature.

As shown in Table 1, the top gas recycling ratio increases in order to the right.

5.3.2. Characteristics of Top Gas Recycling in Total Model

Figure 22 shows the coke rate, reducing agent and carbon input with an intensified recycling ratio of top gas as calculated by the above total model. The base case shows the results of the conventional blast furnace. Figure 22 also shows the recycling ratio of top gas and the energy supply to downstream processes. In Case O-00, reducing agent is higher than in the base case because cold oxygen is supplied to the tuyeres in place of hot blast, which has a high sensible heat. Reducing agent decreases with the recycling ratio, and the coke rate is naturally influenced by PCI. The carbon input decreases with intensified top gas recycling, corresponding to the change in reducing agent. These tendencies agree with the results of Jin and Sahu. However, it should be noted that the energy supply to downstream processes decreases as a result of intensified top gas recycling. This calculation does not include the energy required for CO2 sequestration because a large-scale CO2 sequestration process suitable for the ironmaking process is still in the developmental stage. According to a report on CO2 sequestration, the energy consumption of this sequestration process is estimated to be 2.5–4.0 GJ/t-CO2. If energy demand for CO2 sequestration is considered, the energy supply to downstream processes will decrease even more. Accordingly, although top gas recycling is beneficial for achieving low carbon when only the ironmaking process is considered, the compatibility of this process with the self-completing energy system in the integrated steel works is a practical concern.
5.4. Trials at Commercial Blast Furnace and Experimental Blast Furnace

Short trials of an ironmaking process based on 100% use of oxygen and hot reducing gas injection were carried out at the commercial blast furnace (1 033 m$^3$) at Toulachermet in Russia around the 1990s.\(^{54}\) The process involves blast furnace top gas cleaning, compression, removal of CO$_2$ by chemical absorption, preheating of the gas in the hot stove regenerators and blowing of the gas into the furnace through the tuyeres in place of hot blast. The use of hot reducing gas is accompanied by oxygen injection through each tuyere. There were 13 trials of this technique in the period 1985s–1990s, producing 250 000 t of hot metal. In one particular trial, the coke rate of 367 kg/thm (conventionally, 530–600 kg/thm) was achieved by hot reducing gas injection at a production rate of 1 700 thm/day. Although these tests remained in the trial stage, they provided important reference on matters such as the design of the tuyere structure and control of the flame temperature.

In the ULCOS project, a top gas recycling process based on the oxygen blast furnace was proposed, and its validity was confirmed at the LKAB experimental blast furnace in Lureå.\(^{34–36}\) In this process, most of the top gas is recycled after CO$_2$ removal by VPSA and reheating. Three different versions can be considered, as shown in Fig. 23. In versions 1 and 4, reducing gas derived from the top gas is injected into the lower shaft. Three campaigns were successfully carried out at the LKAB experimental blast furnace (working volume: 8.2 m$^3$). The effect of reducing gas injection on coke and coal savings are illustrated in Fig. 24, showing that the total saving (coke + coal) depends on the total volume of recycled gas.\(^{55}\) In version 3, the saving of coke + coal increased to 78 kg/thm at a recycling ratio of 72%. In version 4, this saving increased further, to 123 kg/thm, at a recycling ratio of 90%. Experiments were performed with recycling ratios up to 90%. In the total steel works, it has been reported that this should result in a CO$_2$ saving of 0.25 GJ/thm, TRZ: Thermal reserve zone.

### Table 1. Calculation conditions for oxygen blast furnace with top gas recycling.

<table>
<thead>
<tr>
<th>Case</th>
<th>Unit</th>
<th>O-00</th>
<th>O-01</th>
<th>O-02</th>
<th>O-03</th>
<th>O-04</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shaft efficiency</td>
<td>–</td>
<td>0.94</td>
<td>0.94</td>
<td>0.94</td>
<td>0.94</td>
<td>0.94</td>
</tr>
<tr>
<td>TRZ temp.</td>
<td>°C</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Burden</td>
<td>Sinter kg/thm</td>
<td>1 274</td>
<td>1 274</td>
<td>1 274</td>
<td>1 274</td>
<td>1 274</td>
</tr>
<tr>
<td></td>
<td>Lumpy ore kg/thm</td>
<td>319</td>
<td>319</td>
<td>319</td>
<td>319</td>
<td>319</td>
</tr>
<tr>
<td>Reducing agent</td>
<td>PCR kg/thm</td>
<td>300</td>
<td>300</td>
<td>200</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Coke rate kg/thm</td>
<td>253</td>
<td>224</td>
<td>284</td>
<td>352</td>
<td>352</td>
</tr>
<tr>
<td></td>
<td>Reducing agent kg/thm</td>
<td>553</td>
<td>524</td>
<td>484</td>
<td>452</td>
<td>452</td>
</tr>
<tr>
<td>Blast condition</td>
<td>Oxygen Nm$^3$/thm</td>
<td>303</td>
<td>287</td>
<td>276</td>
<td>267</td>
<td>267</td>
</tr>
<tr>
<td></td>
<td>Moisture g/Nm$^3$</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Shaft gas Injection</td>
<td>Injection rate Nm$^3$/thm</td>
<td>300</td>
<td>350</td>
<td>350</td>
<td>350</td>
<td>550</td>
</tr>
<tr>
<td></td>
<td>Injection temp. °C</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>CO$_2$ sequestration Nm$^3$/thm</td>
<td>0</td>
<td>184</td>
<td>184</td>
<td>186</td>
<td>258</td>
</tr>
<tr>
<td>Tuyere gas Injection</td>
<td>Injection rate Nm$^3$/thm</td>
<td>60</td>
<td>60</td>
<td>250</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>CO$_2$ sequestration Nm$^3$/thm</td>
<td>0</td>
<td>32</td>
<td>131</td>
<td>213</td>
<td>187</td>
</tr>
<tr>
<td>Top gas recycling ratio</td>
<td>%</td>
<td>30</td>
<td>52</td>
<td>70</td>
<td>82</td>
<td>88</td>
</tr>
<tr>
<td>Specific bosh gas volume</td>
<td>Nm$^3$/thm</td>
<td>857</td>
<td>798</td>
<td>912</td>
<td>989</td>
<td>989</td>
</tr>
<tr>
<td>H$_2$(H$_2$+CO) in bosh gas</td>
<td>%</td>
<td>17</td>
<td>19</td>
<td>15</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Flame temperature °C</td>
<td></td>
<td>2 638</td>
<td>2 738</td>
<td>2 578</td>
<td>2 560</td>
<td>2 563</td>
</tr>
<tr>
<td>Top gas temperature °C</td>
<td></td>
<td>164</td>
<td>126</td>
<td>144</td>
<td>133</td>
<td>238</td>
</tr>
<tr>
<td>Slag volume kg/thm</td>
<td></td>
<td>304</td>
<td>300</td>
<td>298</td>
<td>296</td>
<td>296</td>
</tr>
</tbody>
</table>

Fig. 22. Calculated results for oxygen blast furnace with top gas recycling.
of around 65% at the hot coil level.

6. Further Improvement of Oxygen Blast Furnace

6.1. Calculation Conditions and Concept of Advanced Oxygen Blast Furnace

The oxygen blast furnace shown in Fig. 11(a) was characterized by massive coal injection and a simplified system for preheated gas injection into the upper shaft for heat compensation. Although the basic concept is still valid, further development suitable for injection of gaseous materials such as natural gas is desired considering the current needs for low carbon and energy flexibility. The decomposition heat of the injected natural gas can be just balanced by the pure oxygen supply, which relates to the features of the oxygen blast furnace described above.

In the top gas recycling, it was necessary to use a large amount of shaft gas and co-injection of tuyere gas with pulverized coal and oxygen. Since CO₂ sequestration systems will presumably require sophisticated engineering techniques, construction of the total process may be relatively complicated. Accordingly, a simplified process design which does not sacrifice the advantages of the oxygen blast furnace is desirable. As shown in Fig. 21(b), the advanced oxygen blast furnace is equipped with only preheated gas injection and co-injection of pulverized coal and natural gas, and does not employ a CO₂ sequestration process or top gas recycling. As mentioned in section 5.1, the dynamic behavior in shaft gas injection has a large influence on the effectiveness of top gas recycling, especially in large blast furnaces. However, since the object of preheated gas injection is limited to the supply of sensible heat to control the heat flow ratio in the upper shaft, diffusion of the injected gas to the center is not a serious problem.

In order to clarify the features of the advanced oxygen blast furnace related to energy source flexibility, several calculations were done in the framework of Fig. 20, as shown in Table 2. Cases O-10 to O-13 were calculated using the same values for shaft efficiency, thermal reserve zone temperature and raw material conditions as in Case O-00, and the natural gas and PCI rates were changed to examine the effects of the carbon contents of the injectants on the carbon input to the steel works.

In Cases O-20 to O-23, the shaft efficiency, thermal reserve zone temperature and raw material conditions were set to improved values. It was reported that the permeability in the lower part of blast furnace, in particular, in the cohesive zone, was much improved owing to the accelerated reduction rate resulting from hydrogen derived from natural gas. Wang et al. carried out a series of experiments to study the reduction rate of wüstite in a H₂-CO mixture with an identical gas composition in the oxygen blast furnace process and confirmed the accelerated reduction rate with a high concentration of hydrogen. The experimental results for hydrogen reduction are shown in Fig. 26, which represents the shortening of reduction time in the hydrogen rich condition. The accelerated reduction rate with hydrogen reduction means that the use ratio of low reducibility iron ore such as lumpy ore can be increased. In addition, since hydrogen reduction replaces direct reduction, degradation of coke can be suppressed due to a decrease in the solution loss reaction. Accordingly, the improvement of shaft efficiency can be expected. As favorable results of these above changes, use of low strength and high reactivity coke will be possible, and the thermal reserve zone temperature will decrease. On this matter, the quantitative analysis is required in future.

6.2. Features of Advanced Oxygen Blast Furnace

Figure 27 shows the calculated results of reducing agent, carbon input, the calorific value of BFG and the energy supply to downstream processes. In both Cases O-10 to O-13 and O-20 to O-23, reducing agent gradually decreases as the natural gas injection rate increases. In particular, the carbon input decreases remarkably due to the increased hydrogen input. As mentioned above, the previous oxygen...
blast furnace aimed at massive coal injection and generation of a large amount of gas, and accordingly, input carbon was high. In addition to the decreased carbon input made possible by natural gas injection, the calorific value and hydrogen content of the BFG increase by two times or more in the advanced oxygen blast furnace in comparison with the conventional blast furnace.

Figure 28 shows the relationship between input energy and carbon input to the steel works. Every case except Case O-00 and Case O-10 shows a smaller carbon input than in the conventional blast furnace, and the input energy of Cases O-10, O-20 and O-21 is also lower than that of the conventional blast furnace. Thus, natural gas injection can surely reduce carbon input, however input energy gradually increases with the natural gas injection rate because it is necessary to compensate for the decomposition heat of the natural gas. On the other hand, since the hydrogen included in the natural gas acts advantageously on the material balance of the total reductant, the carbon input decreases.

The hydrogen ratio (H$_2$/(H$_2$+CO)) in the bosh gas is shown in Tables 1 and 2. In the case of top gas recycling in Table 1, the hydrogen ratio is similar to that of the conventional blast furnace. In the advanced oxygen blast furnace, as shown in Table 2, the hydrogen ratio increases up to 41%. In the heat balance, hydrogen reduction of iron oxide has

<table>
<thead>
<tr>
<th>Table 2. Calculation conditions for advanced oxygen blast furnace.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Case</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Shaft efficiency</td>
</tr>
<tr>
<td>TRZ temp.</td>
</tr>
<tr>
<td>Burden</td>
</tr>
<tr>
<td>Lumpy ore kg/thm</td>
</tr>
<tr>
<td>Reducing agent</td>
</tr>
<tr>
<td>Natural gas rate kg/thm</td>
</tr>
<tr>
<td>Coke rate kg/thm</td>
</tr>
<tr>
<td>Reducing agent kg/thm</td>
</tr>
<tr>
<td>Blast condition</td>
</tr>
<tr>
<td>Moisture g/Nm$^3$</td>
</tr>
<tr>
<td>Preheat gas Injection</td>
</tr>
<tr>
<td>Injection temp. °C</td>
</tr>
<tr>
<td>CO$_2$ sequestration Nm$^3$/thm</td>
</tr>
<tr>
<td>Tuyere gas Injection</td>
</tr>
<tr>
<td>CO$_2$ sequestration Nm$^3$/thm</td>
</tr>
<tr>
<td>Specific bosh gas volume Nm$^3$/thm</td>
</tr>
<tr>
<td>H$_2$(H$_2$+CO) in bosh gas %</td>
</tr>
<tr>
<td>Flame temperature °C</td>
</tr>
<tr>
<td>Top gas temperature °C</td>
</tr>
<tr>
<td>Slag volume kg/thm</td>
</tr>
</tbody>
</table>

Fig. 26. Influence of H$_2$ content in gas mixture with various compositions on reduction rate of wüstite.30)

Fig. 27. Calculated results for advanced oxygen blast furnace.
a negative effect due to the endothermic reaction; however, an accelerated reduction rate in the blast furnace can be expected, provided preheating gas is supplied. These situations are shown in Fig. 29 including the direct reduction processes. The MIDREX process, which is a representative direct reduction process based on natural gas, is also considered to be favorable for CO$_2$ mitigation.\textsuperscript{57,58) The expansion of the operating area to a hydrogen-rich gas composition leads to CO$_2$ mitigation.

6.3. Compatibility of Decreased Carbon Input and Excess Energy Supply

Figure 30 shows the relationship between input energy and the energy supply to downstream processes. In the typical integrated steel works, the downstream processes, including rolling mills for producing final steel products, require an energy supply of approximately 4 GJ/thm. The conventional blast furnace can supply just a sufficient amount of energy to these downstream processes. From Fig. 30, it can be understood that excess energy was surely secured except in Cases O-10, O-20 and O21 compared with the conventional blast furnace. In the other cases, excess energy increases with the natural gas injection rate. Natural gas injection changes the heat balance in the lower part of the blast furnace due to the increased decomposition heat of natural gas. Associated with this phenomenon, the increase in input energy produces sufficient excess energy.

As is obvious from Fig. 31, in the case of top gas recycling, the carbon input has a close relationship with excess energy because this process depends on carbon-based reduction of iron oxide. In the top gas recycling process, a reduction of carbon input is achieved at the cost of the energy supply to downstream processes. In contrast to this, in the advanced oxygen blast furnace as represented by the hatched area in Fig. 31, the carbon input tends to decrease even though the energy supply to downstream processes increases. This implies that carbon-based reduction is gradually replaced by hydrogen reduction. Thus, the compatibility of a decreased carbon input and excess energy supply is satisfied in the case of the advanced oxygen blast furnace.

7. Aspects of Next-Generation Blast Furnace

7.1. Comparison of Advanced Oxygen Blast Furnaces with Top Gas Recycling

The distribution of the reduction steps in the blast furnace is shown in Fig. 32. The hatched area including the “Base” case corresponds to the conventional blast furnace condition. Although direct reduction with a low coke rate can be controlled by injectants, the region for the conventional blast furnace is somewhat limited, as shown in Fig. 32, and the change of the reduction step is stagnant because the hot blast contains nitrogen. With intensified top gas recycling, the point corresponding to the reduction distribution moves upward, namely, in parallel with the increase in CO gas reduction, and direct reduction decreases to around 15% at the 89% top gas recycling ratio in Case O-04 in Table 1. In

![Fig. 28. Relationship between input energy and carbon input in advanced oxygen blast furnace.]

![Fig. 29. Gas composition of bosh gas excluding nitrogen in various processes.]

![Fig. 30. Relationship between input energy and energy supply to downstream processes with advanced oxygen blast furnace.]

![Fig. 31. Relationship between energy supply to downstream processes and carbon input with various blast furnace processes.]

1693 © 2016 ISIJ
other words, CO gas reduction just replaces direct reduction. In the advanced oxygen blast furnace with natural gas injection, this point moves to the right. Unlike the top gas recycling process, hydrogen reduction replaces direct reduction in the process with natural gas injection. In Case O-23, the direct reduction ratio closely approaches 0%, while the CO gas reduction ratio remains almost constant. In this critical point, it is expected to suppress degradation of the coke particles in the lower part of the furnace due to the decrease in the solution loss reaction.

Figure 33 shows the relationship between the energy supply to downstream processes and the CO$_2$ emission ratio. In the top gas recycling process, mitigation of CO$_2$ emissions is achieved at the cost of the energy supply to downstream processes. It is estimated that the limit of top gas recycling is substantially equivalent to a 20% reduction in the CO$_2$ emission ratio. However, under this condition, the energy supply to downstream processes approaches 0 GJ/thm. The crucial point in top gas recycling is that it is necessary to provide energy compensation for the downstream processes by securing additional external energy sources. This implies that application of top gas recycling will be limited to certain steel works which have small-scale downstream processes. Since most steel works in Japan have large downstream processes, top gas recycling is not a suitable approach. Figure 33 also shows the CO$_2$ emissions ratio corresponding to the case with CCS (CO$_2$ Capture and Storage). Although a remarkable decrease in CO$_2$ emissions can be expected, CCS requires additional energy and costs, as mentioned above. The technological applicability and economic efficiency of CCS must be solved from the global viewpoint.

Both CO$_2$ mitigation and a sufficient energy supply can be achieved with the advanced oxygen blast furnace in the right part of Fig. 33. As is obvious in Fig. 33, the conventional intensification of the energy supply means an increase in carbon input. However, in the advanced oxygen blast furnace, CO$_2$ mitigation is satisfied by energy conversion to a hydrogen-rich injectant. Especially in Case O-23, the CO$_2$ mitigation ratio reaches a reduction of about 10% in comparison with the conventional blast furnace. The optimum point for CO$_2$ mitigation and energy use will depend selectively on the situation of the actual steel works. For example, depending on the case, excess gas, including hydrogen, can be utilized as available energy for producing electricity at an outside power plant or as a chemical resource.

7.2. Examples of Total Energy Flow

Figure 34 shows the precise examples of the energy flow of several blast furnace processes in integrated steel works, including various facilities, as calculated by the total model in Fig. 20. The ironmaking process includes the coke oven, sintering machine, hot stoves and blast furnace. The power plant generates an adequate quantity of electricity for blowers and the cryogenics process for oxygen production. Electricity and mixed gas of BFG and COG (M-gas) are
recycled to the ironmaking process.

Figure 34(a) shows the conventional blast furnace process (Base), while Fig. 34(b) shows the intensified top gas recycling process based on the oxygen blast furnace (O-04). In this process, input energy is also lower than that of the Base case due to the low carbon input. However, because substantially most of BFG is consumed in the blast furnace by the recycling process, the energy supply to downstream processes is obviously insufficient, which means that energy compensation is required. Although CO$_2$ emissions derived from input carbon apparently decrease, as shown in Fig. 22, actual CO$_2$ emissions must be examined. That is, actual CO$_2$ emissions must be determined by a total evaluation, including carbon associated with energy compensation for downstream processes and the energy required for CO$_2$ capture.

Figure 34(c) shows the advanced oxygen blast furnace based on Case O-04. The feature of this process is compatibility with energy use in the integrated steel works (i.e., maintaining energy self-sufficiency in the total steel works, including downstream processes). Excess gas can be used by outside consumers in an external power plant or as a chemical resource, and the capability of the integrated steel works can be maintained. A similar concept of an oxygen enrichment blast furnace was also proposed by Nakagawa from the viewpoint of a macroscopic process analysis.\(^{59}\)

While maintaining the necessary energy supply, total CO$_2$ emissions based on output carbon were rather lower than in Case O-04 (Fig. 32). Basically, application of a CO$_2$ capture process to the top gas of the advanced oxygen blast furnace is possible in the same manner as in Fig. 21(b), and in this case, further CO$_2$ mitigation can be realized. However, application of CO$_2$ capture is considered to be merely optional.

8. Progressive Development to Next-Generation Blast Furnace

The progressive development to the advanced oxygen blast furnace as a next-generation blast furnace can be represented as shown in Fig. 35. In the advanced oxygen blast furnace, the calorific value of the top gas is approximately two times larger than that in the conventional blast furnace. In particular, the hydrogen content in the top gas is much higher, as shown in Fig. 27, making these gases very valuable for power plants and chemical processes. Moreover, the high productivity of the oxygen blast furnace makes it possible to reduce the furnace inner volume in comparison with a conventional blast furnace with the same pig iron output. In addition, it is estimated that the permeability of the cohesive zone can be greatly improved due to the high hydrogen content of the bosh gas,\(^{56}\) and this will also contribute to improved productivity. The direct reduction ratio is minimized to the limit, and the solution loss reaction also becomes extremely small. Because the smaller inner volume of the advanced oxygen blast furnace reduces the burden stress (load of burden materials) from the upper part, it is possible to relax burden property requirements related to physical strength, i.e., the strength of sintered ore and coke.

As outlined above, the concept of the advanced oxygen blast furnace has the various advantageous features of CO$_2$ mitigation, flexibility of energy use and relaxation of burden properties. According to a study based on a DEM simulation by Takahashi et al.,\(^{24}\) in an oxygen blast furnace with a downsized profile, the maximum compressive stress on the burden is approximately 20–30% smaller than in the conventional blast furnace. This stress reduction means the physical properties of the burden materials can be relaxed, and this relaxation of the burden strength requirements in the oxygen blast furnace will lead to substantial energy savings in the upstream sintering and coking processes. Thus, the advanced oxygen blast furnace has various substantial spillover effects.

In the above study, all the calculations were based on the mass and heat balance model. However, in order to evaluate the operational limitations of actual oxygen blast furnaces, it will be important to make a comprehensive judgment of the distribution of the heat flow ratio, gas and solid temperatures, reduction degree and so on in those furnaces by some kinetic approach. It will also be necessary to design an appropriate injection system for co-injection of pulverized coal/natural gas/oxygen, and the injection limit must be clarified by evaluating combustion properties such as the relationship among the injection rate, combustion efficiency and oxygen enrichment ratio when using such burners. These are the main remaining subjects for future study.

9. Conclusions

Although the blast furnace has been regarded as a highly optimized process which has been realized as a result of various technological improvements, the existing ironmaking process consumes huge quantities of coal and other fossil materials as reducing agents and energy resources. Therefore, continuing innovations to address future circumstances are required. In particular, the next step in the evolution of the blast furnace toward the future should be pursued from the viewpoints of resources, energy and global warming. This review focused on the progressive design of an ambitious blast furnace for the future.

First, the past history of techniques for decreasing reducing agent in the blast furnace, including injection of reducing gas, was reviewed. Although pulverized coal is now commonly used as an injectant, operability for achieving lower coke rates is limited with PCI. To some extent, the low temperature blast furnace based on charging of high reactivity coke is a realistic path to low carbon. The combination of the oxygen blast furnace with top gas recycling is
also attractive. The results of a study of the mass and heat balance of the oxygen blast furnace with top gas recycling showed the advantage of this process for CO2 mitigation. Although the top gas recycling process based on the oxygen blast furnace is very effective for reducing CO2 emissions, a total evaluation of the integrated steel works from the viewpoint of energy self-sufficiency is necessary. The oxygen blast furnace enables injection of a large amount of natural gas in addition to pulverized coal. Optimized injection of natural gas and pulverized coal makes it possible to mitigate CO2 emissions while maintaining the necessary energy supply to downstream processes, and thus satisfies energy consistency in the integrated steel works. Moreover, owing to the high productivity of the oxygen blast furnace, the inner volume of the furnace can be downsized, making it possible to use of low grade burden materials, with accompanying energy savings in the sintering and coking processes. These concepts were summarized as the advanced oxygen blast furnace toward a next-generation ironmaking process.

REFERENCES