ISIJ International, Vol. 46 (2006), No. 12, pp. 1736–1744

Review

Optimization of Ironmaking Process for Reducing CO_2 Emissions in the Integrated Steel Works

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(*Received on April 27, 2006; accepted on June 30, 2006*)

Global warming is a common subject in steel industry in every country. International cooperation will be required using the Kyoto Mechanism from global aspect. In the integrated steel works, there are various means to decrease reducing agent at blast furnace, however, preferable way to reduce CO_2 emissions must be chosen considering energy balance in whole steel works, and energy saving must be actively pursued. Injection of waste plastics and carbon neutral materials such as biomass is better alternative. In the near future, hydrogen will attract attention as a clean energy source even in the steel works. Regarding oxygen blast furnace and smelting reduction, the possibility of CO_2 reduction is dependent on optimum system design of total process including outside process. Charge of prereduced sinter and high reactivity coke to blast furnace leads to reduction of CO_2, keeping current blast furnace facility and capability.

KEY WORDS: blast furnace; global warming; CO_2 reduction; energy balance.

1. Introduction

The Kyoto Protocol took effect in February 2005, and the first agreement period is to begin in the near future in 2008. As declared in the Kyoto Protocol, Japan is targeting a 6% reduction in greenhouse gas (GHG) emissions in 2010 compared with the baseline year 1990. However, according to recent information, Japan's total GHG emissions in 2004 reportedly increased by 7.4% in comparison with 1990, rising to 1.355 billion tons as shown in **Fig. 1**.[1] The breakdown of changes in CO_2 emissions against the baseline year shows a current situation which is characterized by large differences in increases and decreases by area. For example, while emissions in the industry have remained constant, energy consumption increased substantially in the transportation, public and business area, including offices and others, and among households. As a result, there have been calls for further energy saving, accelerated technical innovation in employing currently-unused energy resources, and propagation of energy-efficient equipment and systems. The Japanese steel industry has already targeted a 10.5% reduction in CO_2 emissions under a Voluntary Action Plan adopted by the Japan Iron and Steel Federation and is continuing to make a variety of efforts.[2] Considering the effect

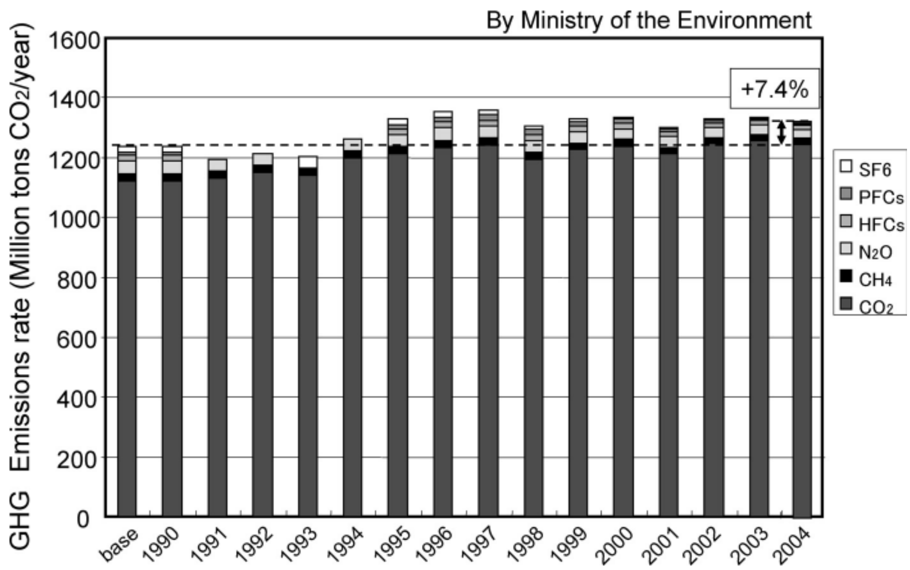


Fig. 1. Trend of Green House Gas emissions in Japan.

of the steel industry on total energy consumption in Japan, the development and deployment of more advanced CO_2 reduction technologies corresponding to increased crude steel production is desirable.

The integrated steel works is a complex system in which huge quantities of coal and other fossil fuels are consumed as reducing agents and fuels in the upstream process of ironmaking, and the gases generated from the ironmaking process are supplied to the downstream processes as energy. In particular, due to the high energy price in Japan, the integrated steel works have actively introduced energy saving equipment, achieving high energy self-sufficiency within the steel works. Because consumption of reducing agents in the upstream process is a major carbon input in an integrated steel works, decreasing consumption of reductants is a basic measure for reducing CO_2 emissions. However, it is always necessary to consider the energy balance in the integrated steel works. For this reason, a systematic study of the steel works as a whole and corresponding countermeasures are necessary.

Then, as the Kyoto Protocol also mentions the international technology transfer as a method of preventing global warming, CO_2 reduction must be considered from a wide perspective. In view of the high technical capabilities which the Japanese steel industry possesses in the area of energy saving, it is essential to consider not only reduction of Japan's own CO_2 emissions, but also international technology transfer and joint implementation through JI (Joint Implementation) and CDM (Clean Development Mechanism) projects under the Kyoto Mechanism. Thus, considering the effectiveness of steel industry efforts on the global scale, it is necessary to examine the total possibilities available to the Japanese steel industry from diverse angles.

Totally, since CO_2 reduction is a common worldwide subject which must be considered in a continuous, long-term manner on the global scale, technical development related to CO_2 reduction is an issue which should be promoted within a large framework by industry as a whole and through international cooperation. Against this background, this paper will describe methods of reducing CO_2 in the iron and steel industry, technical subjects and countermeasures for the integrated steel works and the desirable ironmaking process in the future from the viewpoint of drastic CO_2 reduction.

2. Current State of CO_2 Emissions and CO_2 Reduction Measures in the Steel Industry

As described above, the Japan Iron and Steel Federation (JISF) has established the Voluntary Action Program for environmental protection. The target of CO_2 emissions in 2010 is 10.5% reduction compared with 1990. In this plan, 1.5% additional reduction through the effective use of plastics wastes in blast furnace and coke oven is included.[2] Energy consumption in the steel industry gradually decreased due to the improved energy-saving measures until 2001. However, recently, crude steel production rate in Japan reached over 110 millions tons thanks to the rapid growth in Asian countries. In parallel with this high production rate, reduction of CO_2 emissions are recently stagnant. These situations are shown in **Fig. 2**.

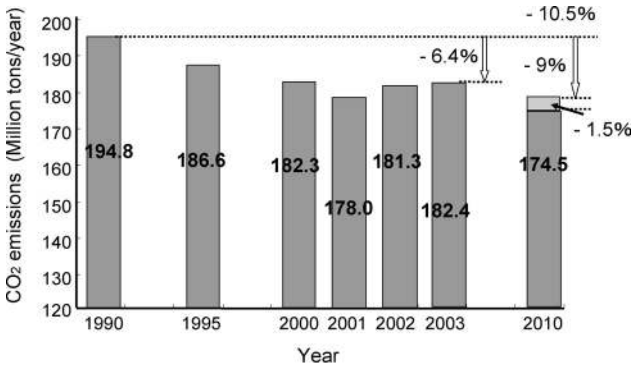


Fig. 2. Trend and target of CO_2 emissions in the Japanese steel industry.

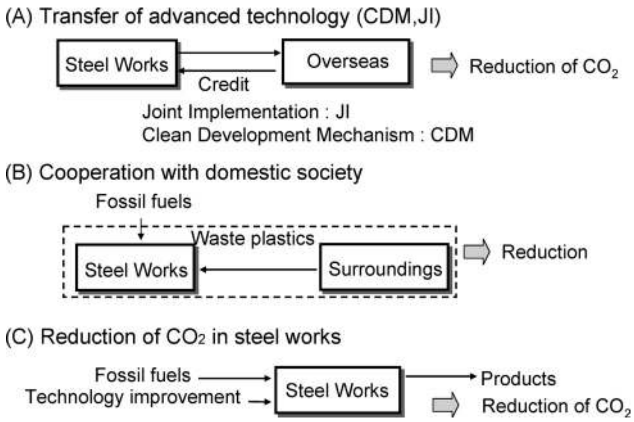


Fig. 3. Possible basic methods of CO_2 reduction in the steel industry.

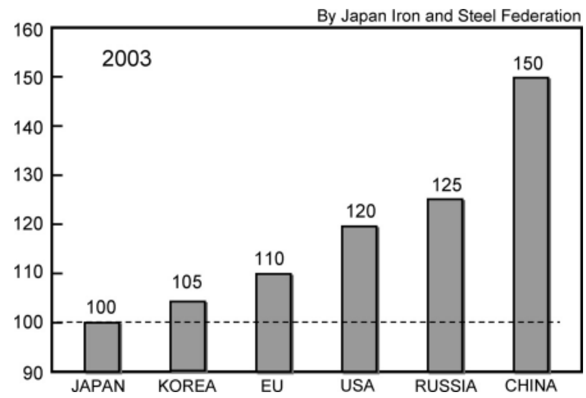


Fig. 4. Comparison of specific energy consumption among major steelmaking nations.

The methods of reducing CO_2 emissions available to the steel industry are shown **Fig. 3**. Figure 3(A) is the well-known method envisioned by the Kyoto Protocol, in which a total reduction in emissions is realized by technology transfer and international or inter-industry cooperation as exemplified by CDM and JI projects, fulfilling the intentions of the Kyoto Mechanism, and the nation providing the technology receives credits (CER: Certified Emission Reduction, EUR: Emission Reduction Unit) for a certain amount of emission reduction. Actually, as shown in **Fig. 4**, energy unit consumption for steel production differs greatly by country. Although CDM is positioned in a complementary role to domestic countermeasures under the Kyoto Protocol, since there are obvious differences in energy consumption between countries, as shown in this figure, positive efforts to reduce CO_2 emissions at the global scale by transferring energy saving technologies are of major significance when seen from the viewpoint of effectiveness in reducing CO_2. Japanese steel industry possesses advanced energy saving technologies and has already proceeded with numerous studies and case studies of technology transfer centering on energy saving technologies such as coke dry quenching (CDQ). However, under the current conditions, in which "additionality" is a requirement in the United Nation responsible for certification, it is difficult to gain international recognition for energy saving technologies as CDM projects. Rather, under the status quo, technologies such as methane recovery and fluorocarbon decomposition which are easily considered in isolation from commercial feasibility are given priority in the approval process. A gradual review of this thinking seems likely in the future, but in any case, energy saving is a method which has a substantial, major effect at the global scale and should basically be promoted with a forward-looking attitude.

Although wastes such as waste plastic are now partly incinerated, methods which utilize these wastes as reducing agents, *etc.* in the steel works are also conceivable, as shown in Fig. 3(B). This is a concept which aims at CO_2 reduction in the social system as a whole (system extension) by reducing consumption of natural fossil materials and reusing the wastes discharged by the general society in industry in a cascade process. Strictly speaking, a life cycle assessment (LCA) is necessary. However, because the cascade method also solves problems related to environmental protection, such as waste disposal, this method has an important ripple effect in domestic society as a whole. Recycling of waste plastic in blast furnaces and coke ovens has already been commercialized[3,4] and is a field where the steel industry can take advantage of its characteristcs. In addition to waste plastic, further extensions of this method are also conceivable, for example, to use of biomass and other carbon neutral substances.

CO_2 reductions within the steel works (Fig. 3(C)) are achieved in parallel with the methods described above. In general, this tends to be explained simplistically as the result of decreasing the reducing agent ratio (RAR) in the blast furnace. However, because changes in the ironmaking process parameters must be preconditioned on the energy balance in the steel works as a whole and the maintenance of steel works functions, as mentioned in the introduction, a technical examination of the effect of these measures is indispensable. In short, the steel industry must confront the problem of effective global warming prevention by making active use of all systems in a comprehensive manner.

3. Carbon Balance in the Integrated Steel Works and Analysis of CO_2 Generation

The carbon balance using the general integrated steel works in Japan is described in this chapter. As in the flow shown in **Fig. 5**, input carbon (X in Fig. 5) in the steel works takes the form of coal, which is converted to coke and consumed as a reducing agent and fuel in the ironmaking process. The coke oven gas (COG) and blast furnace gas (BFG) which are generated simultaneously with this process are supplied to the downstream processes as surplus energy E. Part of this energy is used in the power plant and oxygen plant and returned to the ironmaking process in the form of electric power and oxygen. In other words, input carbon can be expressed as following equation.

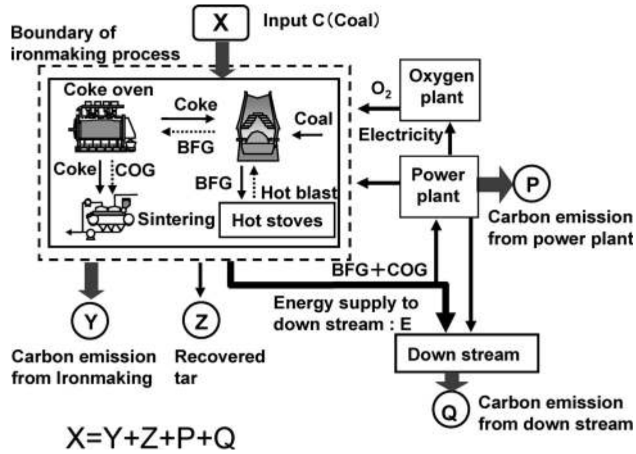


Fig. 5. Carbon balance of the integrated steel works.

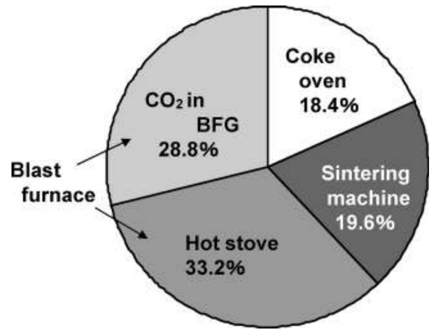


Fig. 6. CO_2 emission from ironmaking process.

$$X=Y+Z+P+Q$$

Output carbon from the steel works is evaluated by Y, P, and Q. Low RAR operation of the blast furnace and other measures to reduce the CO_2 generation must be studied preconditioned on the carbon balance of the steel works as a whole, including all of these factors.

First, looking only at the carbon consumed in the ironmaking process, a reduction of the CO_2 emissions from this carbon is shown in **Fig. 6**. In addition to the CO_2 contained in blast furnace gas, that is, the carbon used in the reduction of iron ore, emissions also include CO_2 from energy consumed by other equipment in the ironmaking process, such as the coke ovens, sintering machines, and hot stoves. Concretely, factors such as the thermal efficiency of the coke ovens and hot stoves and carbon consumption in the sintering process have a direct effect on carbon consumption and CO_2 emissions. Indirectly, the yield of sinter and coke also have an influence. Because low RAR operation tends to reduce supplied energy E, a total evaluation of the steel works is necessary. In contrast to low RAR operation, reduction of carbon consumption in these ironmaking processes is independent of E in Fig. 5 and is directly useful in reducing CO_2 emissions. Among the potential methods of reducing carbon consumption in ironmaking-related processes, reducing power consumption at the oxygen plant has a large effect. At present, the sensible heat of high temperature slag

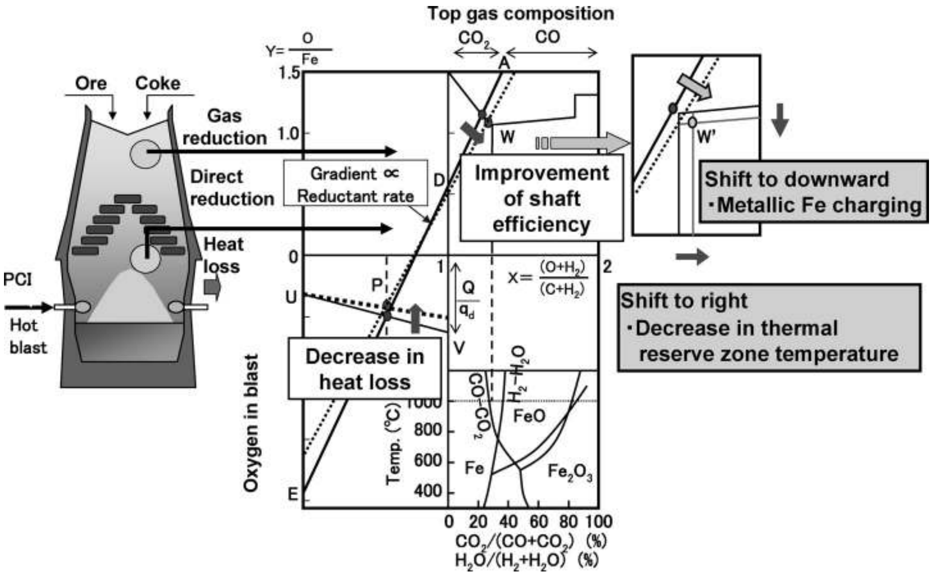
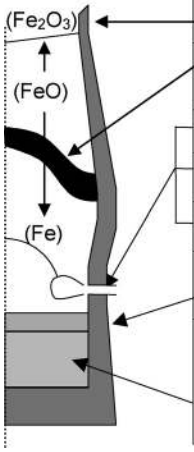


Fig. 7. Concept of reducing agent in blast furnace based on RIST diagram.



	Items	Means
①	Reduction of reducing reaction heat	1) Metallic Fe (Scrap) charging 2) Use of DRI (direct reducing iron)
②	Control of reduction equilibrium	Lowering of thermal reserve zone temperature by use of high reactivity coke
③	Promotion of hydrogen reduction	Injection of waste plastics, NG, etc.
④	Reducing gas injection	COG injection BFG(de-CO_2) injection
⑤	Increase in heat input	Increase in blast temperature Decrease in blast moisture
⑥	Decrease in heat loss	Decrease in heat load to furnace wall by controlling of gas flow distribution
⑦	Decrease in sensible heat of slag and metal	Decrease in hot metal temperature Decrease in slag rate 1) Decrease in coke ash 2) Decrease in gangue 3) Scrap charging

Fig. 8. Measures of low reducing agent rate operation of blast furnace.

is not utilized; however, if this waste heat can be recovered, converted efficiently to power, and used in the steel works, input carbon X can be reduced. The new coke oven, SCOPE 21, which was developed in a Japanese national project concluded in 2003, can achieve a 20% energy saving in comparison with convetional coke ovens, and, if commercialized, it will also have an important effect.[5] Measures which reduce total Y (output C from the ironmaking process) while securing the required E are desirable. When considering low RAR operation, which will be discussed in the following, firstly, positive efforts should be made to reduce carbon consumption in these ironmaking processes, for example, as a direct improvement, by reducing carbon consumption in the sintering machine. Moreover, in order to secure E, it is important to reduce self-consumption in these ironmaking processes so as to keep surplus energy for the downstream processes.

4. Suitable Blast Furnace Operating Conditions for CO_2 Reduction

The concept and measures for reduction of RAR at the blast furnace are shown in **Figs. 7** and **8**.[6] Figure 7 shows the theoretical concept based on a RIST diagram, while Fig. 8 show concrete methods for reducing RAR. Basically, the methods of reducing RAR include shifting the reduction reaction in the blast furnace as close as possible to the equilibrium point and reducing heat loss in the lower part of blast furnace, and shifting the furnace temperature to the low-temperature direction while controlling the reduction equilibrium temperature further toward the oxidation side. The former are realistic methods. Where the latter is concerned, large expectations are placed on future technical development.

The relationship between reduction of RAR and changes in steel works input C when using the RAR reduction methods mentioned above is shown in **Fig. 9**. Here, the evaluation of input C during waste plastic injection is based on the concept of system extension and is therefore considered to be zero. In total, input C naturally decreases as RAR is reduced. In the case of pulverized coal injection (PCI), RAR increases but input C decreases somewhat due to the decrease in coking heat requirements and the increased hydrogen input from the pulverized coal.

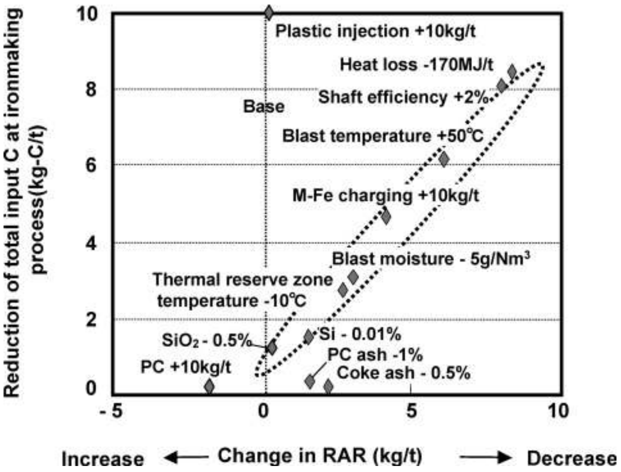


Fig. 9. Relationship between reducing agent ratio and input carbon at ironmaking process.

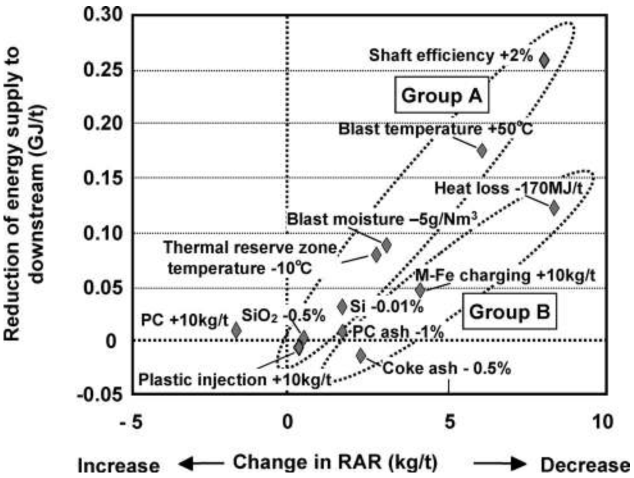


Fig. 10. Relationship between reducing agent ratio and energy supply to down stream.

Next, **Fig. 10** shows the relationship between low RAR operation and the reduction of energy supplied to the downstream processes. In parallel with the move toward low RAR operation, BFG generation is reduced and the amount of supplied energy decreases due to increased furnace top gas oxidation. The effect on energy supplied to the downstream processes is summarized and divided into two groups (Group A and B) based on these blast furnace operating conditions, as shown in Fig. 10. In order to keep energy balance of integrated steel works, priority should be given to selecting the methods in Group B which have a relatively smaller effect on supplied energy, such as reduction of heat loss, *etc.* as shown in Fig. 10, simultaneously with energy saving in the downstream processes.

As an additional note regarding the method of reducing RAR by shifting the furnace temperature to the low temperature side and controlling the reduction equilibrium temperature closer to the oxidation direction, this is thought to be effective for reducing the starting temperature of the coke solution loss reaction. Specifically, it is possible to control the temperature in the furnace by using high reactivity coke. Focusing on this point, research on efforts to realize high reactivity in coke, either by blending coal with a high Ca content or producing coke containing metallic iron, and utilizing the catalytic effect of this material has been reported.[7–9] The former has reached the stage of demonstration tests in an actual blast furnace. Although the idea of reducing RAR by increasing the reactivity of coke was proposed by Rist *et al.* in France, experimental verification and development into a production technology are being carried out in Japan. This is an important subject which should be actively pursued, including control technology on permeability of the lower part of the blast furnace.

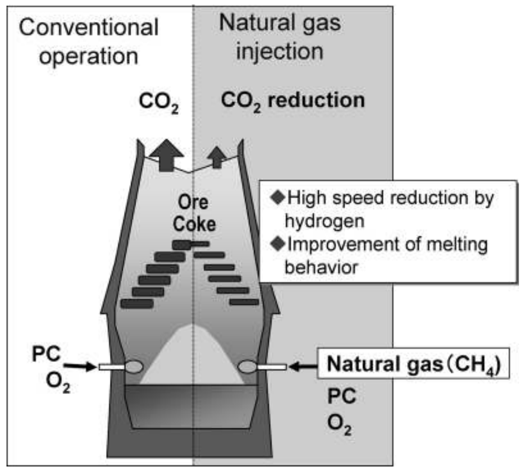


Fig. 11. Effect of natural gas injection in the blast furnace.

5. Future Direction of Blast Furnace Operation

It should be mentioned that JFE Steel's East Japan Works (Keihin District) is currently injecting hydrogen-rich city gas (LNG base) and is evaluating this technique (**Fig. 11**).[10] Outside of Japan, natural gas injection into the blast furnaces is already being used at steel works with easy access to natural gas resources. While this technology is definitely not advantageous in Japan from the viewpoint of natural gas cost, it has a positive effect in that it enables high speed reduction by strengthening hydrogen reduction and facilitates increased production when used in combination with oxygen enrichment. This technology can therefore be expected to attract attention in the future as a method which enables efficient production increases and CO_2 reductions at steel works located near natural gas supply station even in Japan.

The basic principle is to reduce CO_2 in an energy self-sufficient type system by reducing energy consumption in the ironmaking process and adopting proper blast furnace operating conditions. Simultaneously, energy saving in the downstream processes must be implemented to the maximum extent possible. However, as energy saving in the integrated steel works as a whole approach its limits, it is also necessary to consider supplementary energy sources for the downstream processes. In cases where the steel works is located in an industrial complex near other factories, total CO_2 reduction by promoting mutually-complementary energy sources through cooperation within the industrial complex will also be important; this includes measures to facilitate access to hydrogen-based energy and other types of clean energy and the use currently-unused energy resources. Thus, it appears that the possibility of utilizing hydrogen-based natural gas in Japan, for example, in CO_2 re-

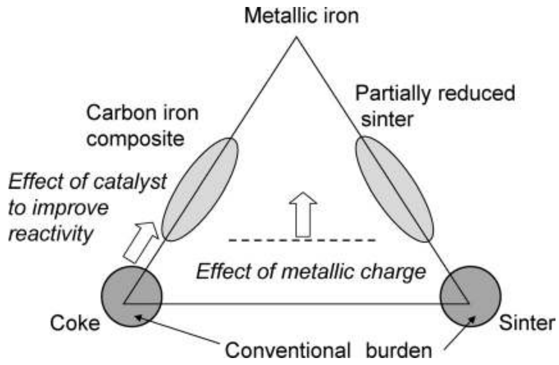


Fig. 12. Conception of new burden material to decrease reducing agent in blast furnace.

duction by injection of hydrogen-based reducing agents in the blast furnace and the use of clean natural gas as a heat source for various applications, will play an important role in the development of large CO_2 reduction measures.

6. CO_2 Reduction by Evolutionary Development of the Ironmaking Process

The ironmaking process, comprising the coke ovens, sintering machine, blast furnace, and auxiliary equipment, accounts for the largest input of fossil fuels in the steel works. Broadly speaking, ironmaking functions are currently divided among the coke ovens, where coal is carbonized, the sintering machine, where fine iron ore is agglomerated, and the blast furnace, where the iron ore is reduced and melted. If efficient reduction can be achieved in the pretreatment process by distributing the reduction function to processes other than the blast furnace, it will be possible to reduce the load on the blast furnace and thereby reduce the required RAR. In addition to conventional sinter, agglomerates partially reduced and coke including metallic iron can be considered as new burden material to reduce reducing agent of blast furnace. This conception can be shown in **Fig. 12**.

A process in which fine ore is partially reduced simultaneously with agglomeration in the sintering machine is currently under development with the intention of realizing the above-mentioned distribution of functions.[11] The concept of this partial reduction process is shown in **Fig. 13**. Partial reduction is achieved in the sintering machine by an additional internal carbon material (Fine coke) as reductant in the quasi-particles besides external carbon coating as heat source. Because iron ore is reduced in the blast furnace mainly by gas reduction, restrictions related to the gas reduction equilibrium will always exist. However, with this method, reduction proceeds by solid reduction with no equilibrium restrictions because carbon material is coated on the ore particles. Furthermore, the generated gas is also used as a heat source, making it possible to complete the process with a smaller amount of carbon. When this pre-reduced sintered ore is charged into the blast furnace, RAR can be greatly reduced, resulting in a reduction in carbon consumption in the ironmaking process as a whole. **Figure 14** shows the relationship between the partial reduction ratio of sintered ore and the total carbon consumption of the blast furnace, sintering machine, and coke ovens. If a reduction ratio of 40% or higher is achieved, total carbon

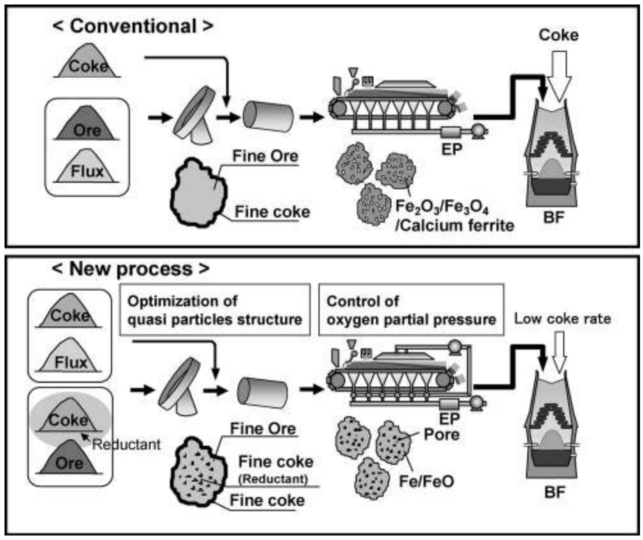


Fig. 13. Production process of partially reducuced sinter based on sintering machine.

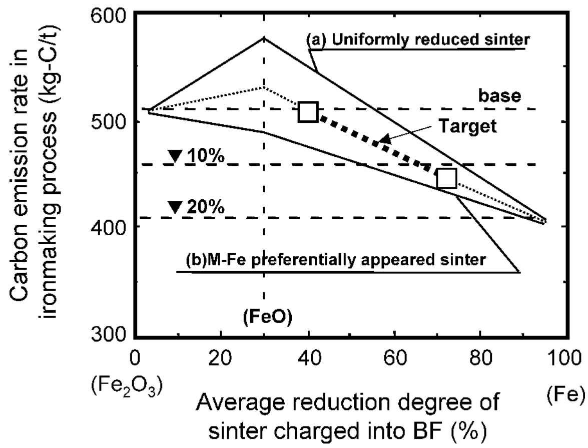


Fig. 14. Effect of prereduced sinter charge into blast furnace.

consumption shows a decreasing tendency. The proposal for a process based on the oxygen blast furnace, which will be discussed in the following, will require large scale modifications in the existing process, including the installation of auxiliary equipment such as top gas recycling, but with the process described above, the existing blast furnace, which is the basic equipment, can be used without change and there appear to be few problems related to equipment technology.

Second one is the carbon iron composite. The carbon iron composite means coke containing metallic iron. **Figure 15** shows the effect of high reactivity coke containing metallic iron (carbon iron composite) on the basis of Rist diagram. Metallic iron has an effect to control of thermal reserve temperature as catalyst and metallic charge to blast furnace.[12] It is evaluated that such a carbon iron composite can be produced in the shaft-type furnace instead of conventional coke oven. In Japan, since conventional coke oven is older than foreign countries like Europe, the renewal of coke oven will be a serious subject in the near future. New concept coke oven will be so required as to solve environmental problem such as CO_2 reduction. By carbon iron composite, reducing agent of blast furnace can be reduced by control of thermal reserve temperature and metallic

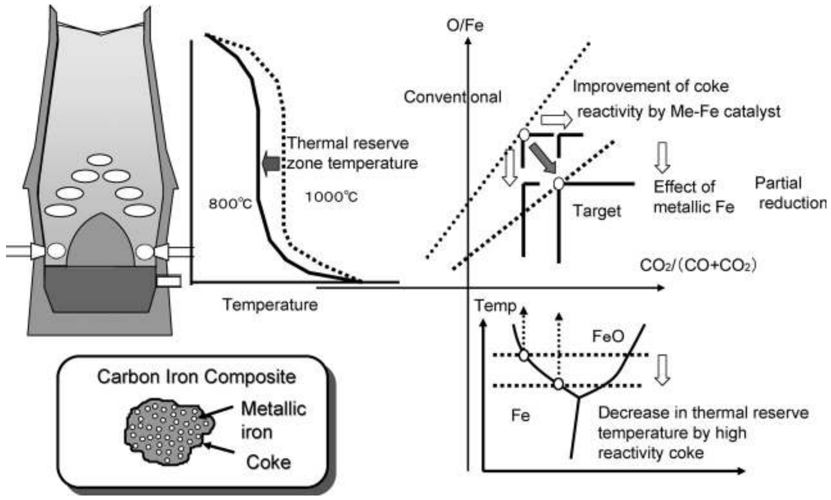


Fig. 15. Effect of high reactivity coke containing metallic iron (carbon iron composite) on blast furnace.

charge, keeping the basic blast furnace facility and capability, CO_2 reduction can be effectively attained.

7. Evaluation of Desirable Future Ironmaking Process on CO_2 Reduction

Up to this point, this study has focused on the existing blast furnace. From the future perspective, this section will examine CO_2 reduction by evolutionary systems such as the oxygen blast furnace (nitrogen-free blast furnace), which attempt to improve the functions of the blast furnace. Rather than blowing hot blast, as in the conventional process, the oxygen blast furnace is a process in which nitrogen-free cold oxygen (normal temperature) is blown into the furnace through the tuyeres. As shown in **Fig. 16**, productivity improvement is possible and low coke ratio operation is easily achieved by high rate injection of pulverized coal. Although there have been several examples of study of the oxygen blast furnace in countries outside of Japan, in all cases these were limited to desktop simulations. In Japan, JFE Steel has carried out demonstration tests of the oxygen blast furnace with an experimental blast furnace and oxygen burner tests with an actual blast furnace.[13)]

A comparison of the required input *C* with the conventional blast furnace, oxygen blast furnace, and a smelting reduction process (DIOS) was obtained by model calculations based on typical operating parameters, with the results shown in **Fig. 17**. The calculation results showed that the oxygen blast furnace has various advantages such as reduced blast furnace heat loss and reduction at low temperature, but because it also has the drawback of higher electric power energy requirements due the large quantity of oxygen supplied, in total, there is no large change from the conventional blast furnace. With the smelting reduction process, the results vary depending on the post-combustion ratio, but there are technical limits to the post-combustion ratio. Because the generated gas can be utilized effectively in the surrounding society, an evaluation based on the surrounding society as a whole becomes a key point. With the oxygen blast furnace, application of CO_2 sequestration is easier than with the conventional blast furnace because the generated gas is nitrogen-free. Thus, if application of CO_2 sequestration on an industrial scale becomes possible in the

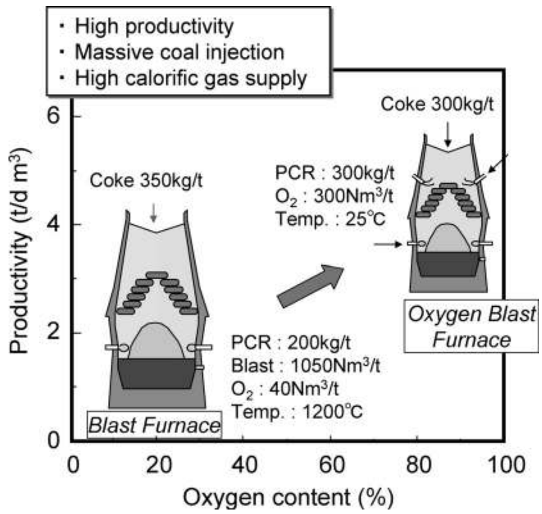
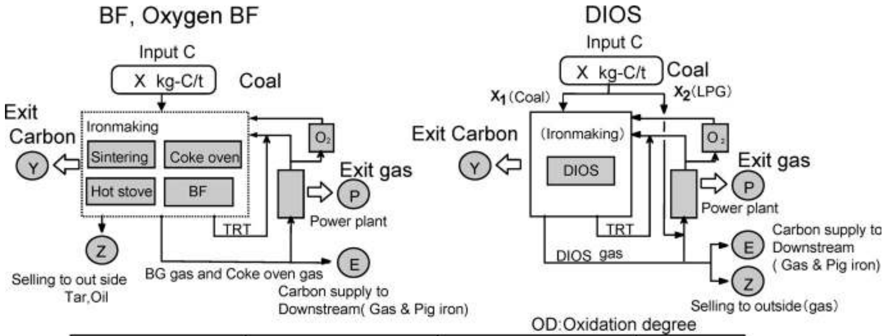


Fig. 16. Feature of oxygen blast furnace.

future, various methods of achieving large CO_2 reductions are conceivable.

Figure 18 shows two examples of processes in which CO_2 sequestration is added to the oxygen blast furnace as the basic process. The unutilized CO in the blast furnace top gas can be recycled as a carbon source for the blast furnace so that a large reduction in input *C* can be expected.

Figure 19 shows the relationship between input *C* to the ironmaking process in these processes and the energy supplied to the downstream processes. As mentioned above, a CO_2 reduction of approximately 15% can be expected as a result of circulating use of unused CO with CO_2 sequestration. It should be noted that the additional energy for preheating the circulated gas is not included in this evaluation. Looking only at this figure, supplied energy is substantially reduced. This means that realization of thoroughgoing energy saving in the downstream processes and introduction of economical hydrogen-based energy for makeup are preconditions for these methods. If these conditions can be provided, these technologies can be considered candidates for large CO_2 reduction processes in the future. In any case, however, whether it is possible to introduce large-scale CO_2 sequestration and storage processes which can be applied to the steel manufacturing process or not will have an impor-



	BF Case 1	BF Case 2	Oxygen blast furnace Case 1	Oxygen blast furnace Case 2	DIOS
PCR (kg/t)	150	200	300	300	OD 38.4
Shaft efficiency (-)	0.92	0.92	0.92	0.85	
Heat loss (10^4kcal)	20	20	20	20	
TRZ (°C)	950	950	750	750	
X (kg/t)	**545**	**542**	**534**	**565**	**578**
Y (kg/t)	241	228	117	118	30
P (kg/t)	34	37	143	147	156
E (kg/t)/(Gcal/t)	250/1.0	260/1.0	259/0.79	285/1.0	317/1.0
Z (kg/t)	19	18	14	15	75
Net exit C (kg/t) (X-Z)	**526**	**524**	**520**	**550**	**503**

Fig. 17. Comparison of various ironmaking process on carbon consumption.

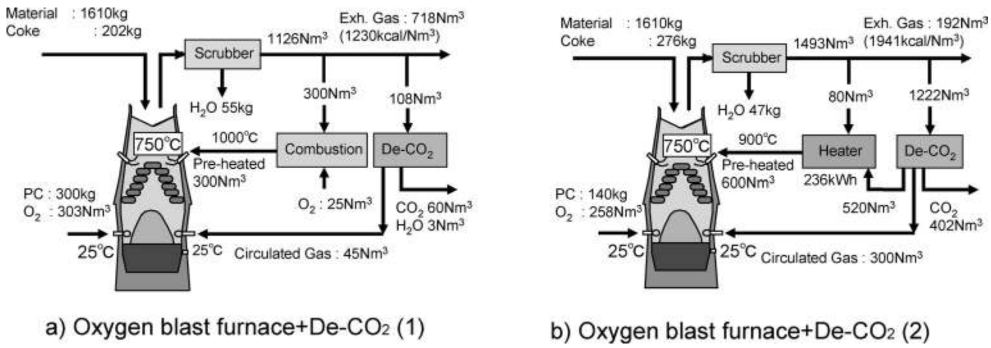


Fig. 18. Material balance of oxygen blast furnace equipped with sequestration process.

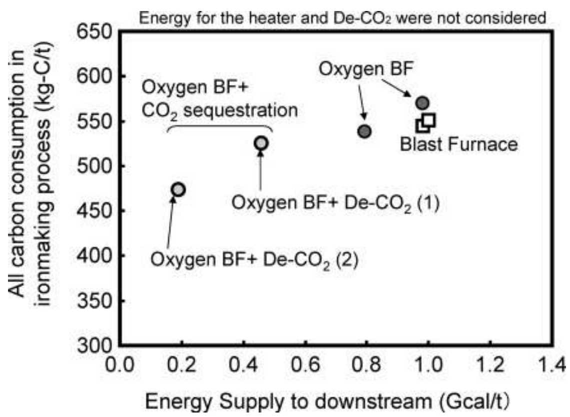


Fig. 19. Carbon consumption and energy supply to down stream in various processes.

tant influence.

5. Conclusion

There still remain subjects regarding reduction of CO_2 emissions in steel industry. Firstly, transfer of advanced technology as to energy saving should be pursued to make use of the conception of the Kyoto Mechanism. Although there are various means to decrease reducing agent at blast furnace, preferable way to reduce CO_2 emissions must be chosen considering energy balance in whole steel works. Energy saving must be actively pursued to keep energy balance and decrease energy makeup in the downstream. Injection of waste plastics and carbon neutral materials such as biomass is better alternative. Hydrogen-based ironmaking process will attract attention even in Japan.

Oxygen blast furnace and smelting reduction process have a similar level in carbon consumption to current blast furnace. In such a process, the possibility of CO_2 reduction is dependent on optimum system design of total process including outside process. However, oxygen blast furnace is favorable to reduce CO_2, if CO_2 capture and storage are installed in ironmaking process. Charge of prereduced sinter and high reactivity coke such as carbon ore composite leads to reduction of CO_2 emissions, keeping current blast furnace facility and capability.

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