

Reduction of CO₂ Emissions from Integrated Steel Works and Its Subjects for a Future Study

Tatsuro ARIYAMA, Ryota MURAI,¹⁾ Jun ISHII¹⁾ and Michitaka SATO¹⁾

Steel Research Laboratory, JFE Steel Corporation, Kawasaki-cho, Chuo-ku, Chiba 260-0835 Japan.

1) Steel Research Laboratory, JFE Steel Corporation, 1, Kokan-cho, Fukuyama, Hiroshima 721-8510 Japan.

(Received on March 4, 2005; accepted on July 14, 2005)

Reduction of CO₂ emissions has been discussed using newly developed precise model based on carbon and energy balance in large-scale integrated steel works as a whole. Although there are various means to decrease reducing agent rate (RAR) at blast furnace, preferable way to reduce CO₂ emissions must be chosen considering energy balance in whole steel works. Reduction of RAR at blast furnace together with energy saving at downstream processes is important. Maintaining competitiveness in global steel market must be also considered. Simple reduction of RAR such as improvement of shaft efficiency at blast furnace without energy saving at downstream processes leads to increase in production cost because of increment of purchased energy. Injection of waste plastics and carbon neutral materials such as biomass is better alternative.

Regarding blast furnace operation, under the use of inferior raw materials such as low strength coke as well as high productivity condition, there are many problems to be solved to achieve low RAR operation. It has been reported that drastic change of lower part situation such as increase in coke degradation and accumulation of coke fine causes operation instability at actual blast furnace. Therefore, to attain stable low RAR operation, it is confirmed that new control measures based on fundamental researches to solve various problems should be developed.

KEY WORDS: CO₂ emissions; integrated steel works; blast furnace; reducing agent rate; carbon neutral; energy saving.

1. Introduction

According to recent reports, Japan's total CO₂ emissions have gradually increased, and in order to achieve the country's reduction target declared in the Kyoto Protocol, there remain some subjects to be solved. This increase is attributable to the general public and transportation areas, and although manufacturing industries have shown satisfactory progress in comparison with other areas as a result of various efforts, including energy saving, Japanese steel industry is making an effort to decrease CO₂ emissions based on a recognition of its effect on emissions. Japan Iron and Steel Federation has set a 10.5% reduction target under a Voluntary Action Plan.¹⁾

In producing steel products, ironmaking process of integrated steel works consumes large quantities of fossil fuels as a heat source and reducing agent and supplies the generated energy to downstream processes as an energy source, totally forming a self-completing system based on optimum energy balance. Thus, it is complicated to reduce CO₂ emissions because of close relation with the consumption of carbon, which is indispensable for reducing iron ore besides energy consumption. It is necessary to seek the optimum solution, taking into account support of steel works functions.

From the above backgrounds, blast furnace operation in Japan should basically move towards low reducing agent rate (RAR) operation, and it must be done with high ratio of inexpensive raw materials, considering the production cost and energy balance of integrated steel works. This situation is different from other countries in regard to burden material and energy conditions. This will be a new subject for Japanese steel industry. This paper describes methods of reducing CO₂ emissions in the steel industry, presents a model of the carbon balance in the steel works and discusses subjects to be solved in blast furnace operation from the viewpoint of CO₂ reduction.

2. Basic Conception of Countermeasures for CO₂ Reduction in Steel Industry

As general considerations, the basic methods of reducing CO₂ are outlined in Fig. 1. Figure 1(A) is the well-known method of reducing total emissions through technology exports and international cooperation, and receiving credits for a certain amount of CO₂ reductions as a result of these efforts, as exemplified in JI (Joint Implementation) and CDM (Clean Development Mechanism) under the Kyoto Mechanism. In the steel industry, many possibilities like CDQ and other plants for energy saving have already been

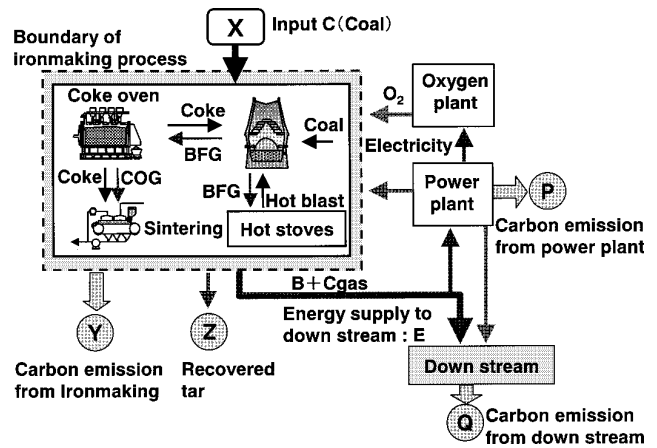
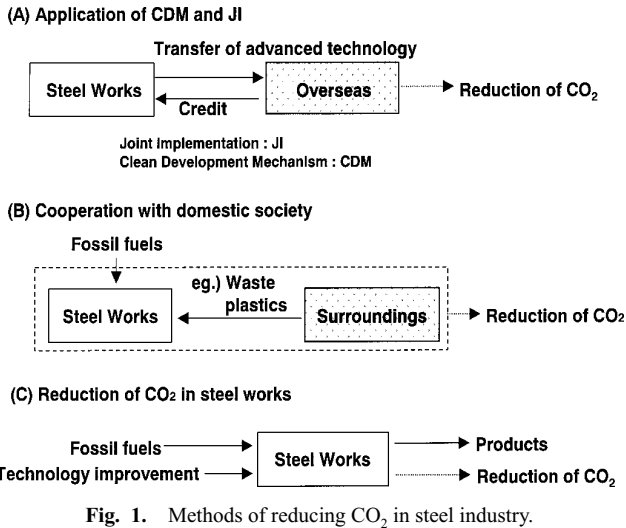


Fig. 2. Carbon flow in typical integrated steel works.

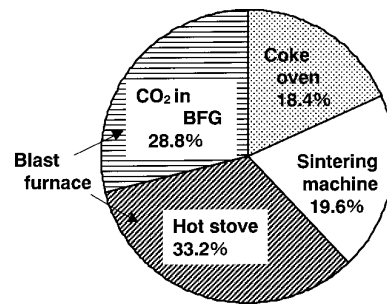


Fig. 3. CO₂ emission from ironmaking process.

studied. Unit energy consumption for iron and steel production differs greatly depending on the country. In Japan, high levels of energy saving by various advanced technologies have been already attained, and, for other countries, such outstanding energy saving technologies have great value as global warming countermeasures. Transfer of advanced technology as to energy saving should be pursued to make use of the conception of the Kyoto Mechanism.

Use of wastes which are simply incinerated at present can be one conceivable method of reducing CO₂ in the social system as a whole, if they are effectively used as a reducing agent in the steel works. Figure 1(B) shows use of waste plastic as an example of this method. Strictly speaking, life cycle assessment (LCA) on efficiency of recycling is needed, however, since this method currently contributes to the creation of a recycling-oriented society, it is an attractive basis as a new activity of steel industry. Use of waste plastic as reducing agent for blast furnace has been already commercialized.²⁾ Further expansion of this method to include carbon neutral materials such as biomass should also be considered in the future. Because the biomass produced in Japan is equivalent to 2.8% of the country's primary energy consumption,³⁾ use of this resource cannot be ignored.

In parallel with these methods, CO₂ reduction in the framework of steel works is also important. In general, it seems to be easy to make simplistic proposals for reducing the rate of reducing agents in the blast furnace, however measures must be preconditioned on maintaining the functions of the steel works based on energy balance. The problem of preventing global warming must be confronted by comprehensive use of all available systems.

3. Carbon Balance and CO₂ Generation from Integrated Steel Works

This chapter examines the carbon balance based on the general integrated steel works in Japan as a model. As shown in the flowchart in Fig. 2, input carbon, C, is input into the steel works as coal (X in Fig. 2) and is consumed as a reducing agent and heat source in the ironmaking process. At the same time, this generates excess energy, E, which is supplied to downstream processes as C-gas (coke oven gas)

and B-gas (blast furnace gas). Part of this energy is consumed by the power plant and oxygen plant and returned to the ironmaking process as electricity and oxygen. This means that input C(X) can be expressed as follows:

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

Therefore, C emissions from the steel works are evaluated by Y (emissions from the ironmaking processes), P (emissions from power generation), and Q (emissions from downstream processes). Although operation of the blast furnace with a low reducing agent rate will be the main object of study for reduction of CO₂ emissions, study must also consider this model of the carbon balance in the steel works as a whole.

Figure 3 shows CO₂ emissions limited to the ironmaking processes (Y in Fig. 2). In addition to CO₂ emissions in blast furnace gas, energy consumption in other ironmaking processes such as coke ovens, sintering machines and hot stoves is also a source of emissions. Low RAR operation at the blast furnace is directly related to reduced supplied energy, E, in the works. On the other hand, coke ovens, sintering machines and hot stoves independently consume energy, then, in contrast to the blast furnace, improvement in the heat balance of these processes reduces CO₂ emissions without affecting E in Fig. 2. Yield improvement in the sintering and cokemaking processes is also substantial, and reduced unit power consumption by oxygen plants would also have a significant effect. Measures which reduce CO₂ emissions from the ironmaking process (Y), while maintaining a certain level of energy (E) as far as possible, are desirable. In other words, it is important to reduce firstly energy consumption in the ironmaking processes, as shown in

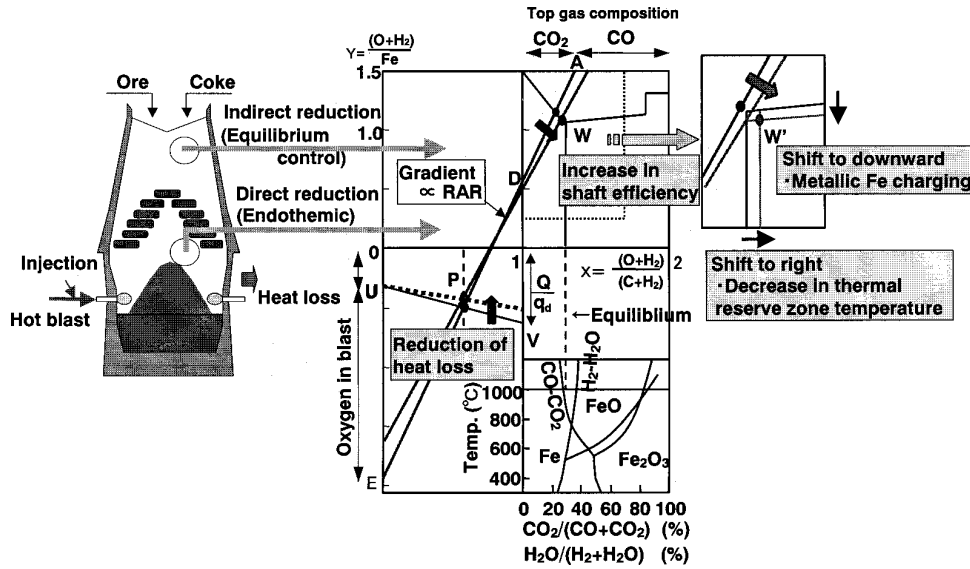


Fig. 4. Concept of reducing agent rate reduction based on RIST diagram.

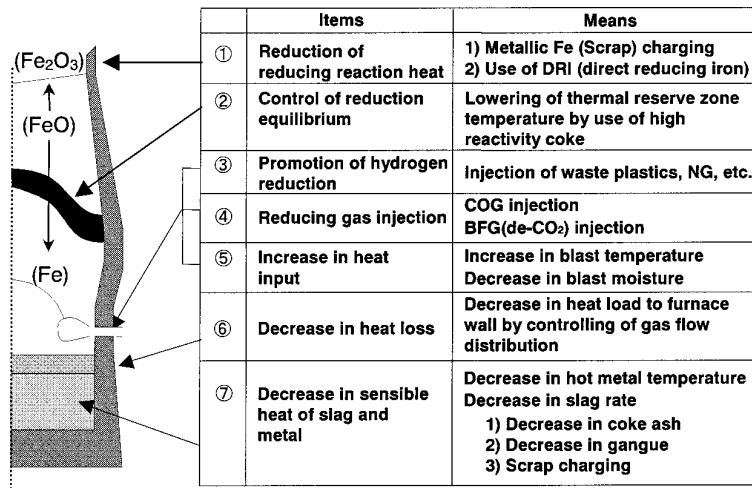


Fig. 5. Measures of low reducing agent rate operation of blast furnace.

Fig. 3, and consider measures which make it possible to operate the blast furnace at a low RAR while continuing to produce an adequate margin of energy for the downstream processes.

4. Blast Furnace Operation for CO₂ Reduction

The concept and measures for low RAR operation of the blast furnace as an independent unit are shown in Figs. 4 and 5. Figure 4 shows the concept of low RAR operations based on RIST diagram, and Fig. 5 shows concrete measures including future technologies under development. Basically, measures for low RAR operation consist of improvement of shaft efficiency, charge of metallic iron, reduction of the heat loss in the lower part of blast furnace, and furthermore, control of the reduction equilibrium on FeO/Fe. The improvement of shaft efficiency, heat balance and charge of metallic iron are realistic, whereas control of the reduction equilibrium relatively depend on future technical developments such as use of high reactivity coke. However, in either case, every low RAR operation of blast furnace should be positively appreciated, and at the same

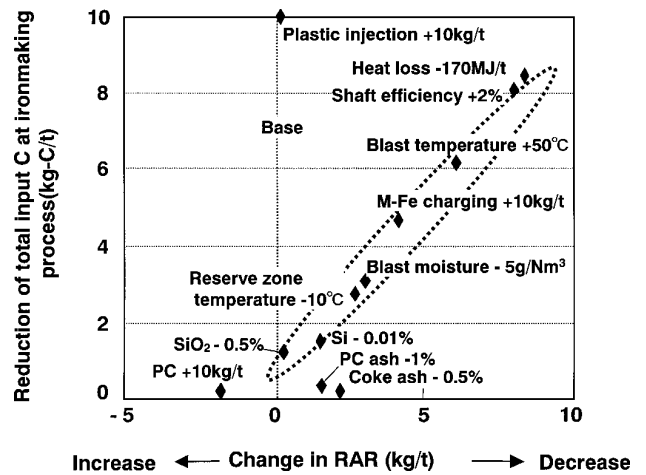


Fig. 6. Relationship between RAR and total input C at ironmaking process.

time it is still necessary to study the system as whole in order to evaluate the effect of CO₂ reduction in the integrated steel works, as discussed in Chap. 3.

Figure 6 shows the relationship between total input C at

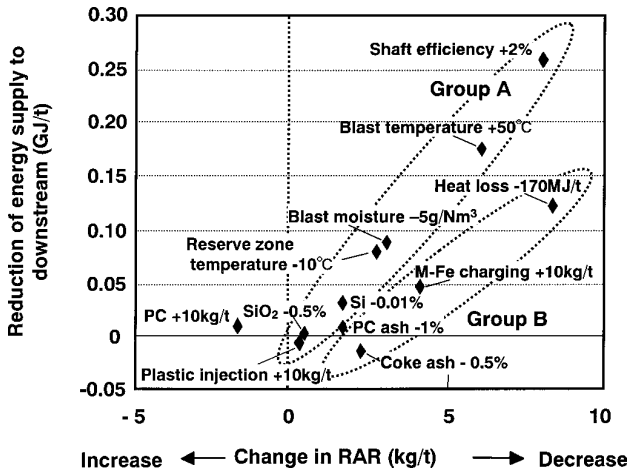


Fig. 7. Relationship between RAR and energy supply to downstream.

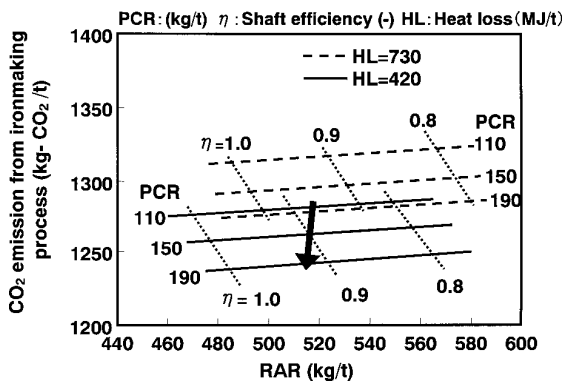


Fig. 8. Effect of heat loss, shaft efficiency and PCR on CO₂ emission from ironmaking process.

ironmaking process and reduction of RAR in the main low RAR measures for the blast furnace. Here, the evaluation of input C with waste plastic feed is assumed to be zero. Total input C decreases as RAR decreases. In the case of pulverized coal injection (PCI), RAR increases, however total input C shows a slight decrease. RAR increases because the coke replacement ratio of pulverized coal is less than 1.0, while total input C decreases due to reduced coke production and an increase in hydrogen input by using pulverized coal. The relationship to the reduction in energy supplied to downstream processes is shown in Fig. 7. Supplied energy decreases in parallel with the trend toward low RAR operation. The change in RAR and reduction in supplied energy through changes in the B-gas utilization ratio can be divided into two groups (Group A, B). If preservation of downstream process functions is considered to be indispensable, priority should be given to selection of a method which has little effect on supplied energy, such as reduction of heat loss, as shown in the lower Group B in Fig. 7, simultaneously with energy saving in the downstream processes. Figure 8 shows the relationship between blast furnace operation design factors as determined by model calculations and C emissions in the ironmaking processes (Y in Fig. 2), where the PCI rate and heat loss are the main parameters. It can be understood from this figure that, in order to reduce heat loss while making the maximum use of PCI, as described above, it is desirable to shift the operation point as far downward as possible. This is the direction in which the

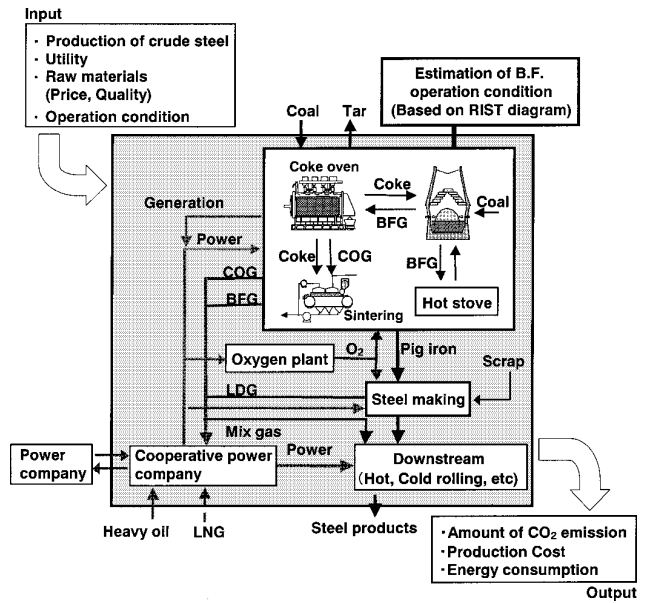


Fig. 9. Structure of CO₂ balance calculation model in integrated steel works.

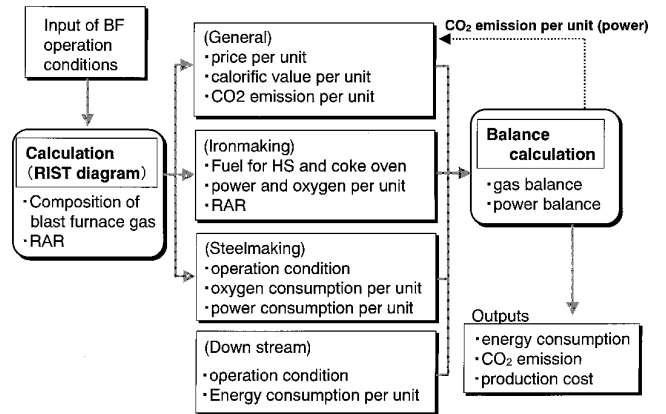


Fig. 10. Calculation flow and control factors of CO₂ balance model in integrated steel works.

PCI rate is increased and heat loss in the lower part of blast furnace is reduced. Actually, it is difficult to achieve both simultaneously. However, in future, the establishment of these technologies will be a major target in ironmaking from the viewpoint of CO₂ reduction, followed by improvement of burden properties, accurate control of the burden distribution and direct control of permeability in the lower part of blast furnace.

5. Precise Evaluation of CO₂ Reduction in Actual Steel Works

Here, a precise model of the CO₂ emission in the steel works for a large-scale integrated steel works is proposed to clarify the effect of low RAR operation on CO₂ emission in the steel works. The structure of this model is shown in Fig. 9, and represents accurately a typical integrated steel works. The model structure and factors considered in ironmaking, steelmaking and downstream processes are shown in Fig. 10. Although these structures will differ depending on the local conditions and product mix of the individual steel works, it is thought that the integrated steel works can basi-

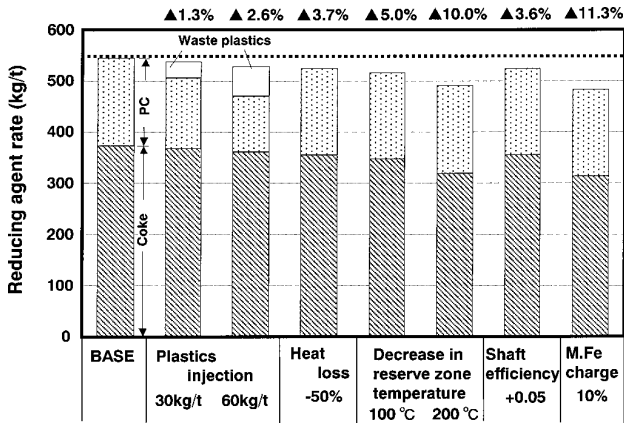


Fig. 11. Relationship between various blast furnace operating conditions and reducing agent rate.

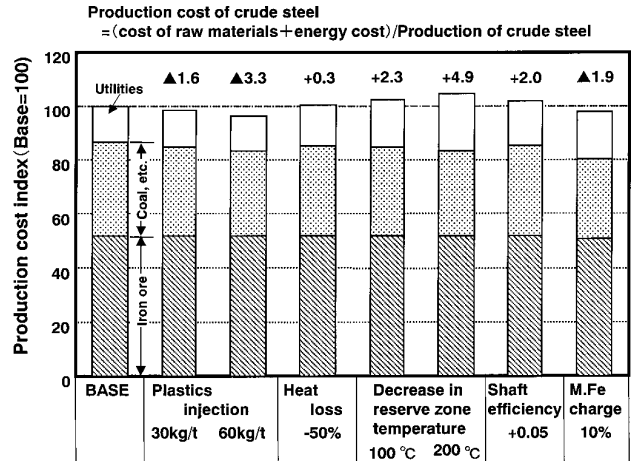


Fig. 13. Effect of operation condition of blast furnace on production cost.

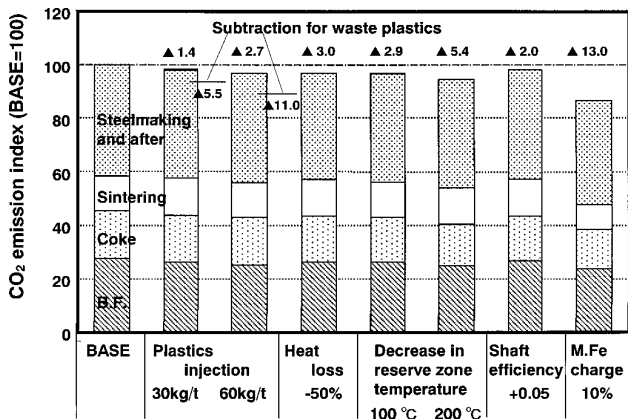


Fig. 12. Calculation results of CO₂ emissions from the integrated steel works.

cally be expressed by these models. The model which includes steelmaking and subsequent processes reflected the operating conditions of various types of furnaces and other equipment comprising each shop in the actual steel works. Here, the boundary region with the surrounding society includes the power plant. Conditions were set assuming a constant uninterrupted supply of power to the system in the steel works. Therefore, shortages in the energy supply from within the works are covered with purchased energy (heavy oil, etc.) from outside. CO₂ emissions associated with power generation were assigned to each power-consuming process.

First, the relationship between various blast furnace operating conditions and RAR is shown in Fig. 11. From the mid- and long-term viewpoints, a wide range of variation in the operating conditions was assumed, however as in conventional evaluations, in addition to metal charging, the effect of reducing the thermal reserve zone temperature is large. It can also be quantitatively understood that waste plastic feed has a large effect in reducing CO₂. Next, Fig. 12 shows the results of a calculation of CO₂ emissions from the steel works as a whole by the model described above. Shifting to low RAR operation of the blast furnace reduces energy supplied to the works by the ironmaking process. However, as a total effect, CO₂ emissions in the steel works as a whole can be reduced by using high-calorie purchased energy or hydrogen-rich energy like Natural Gas. An evaluation of the CO₂ reduction effect is shown in Fig. 13, to-

gether with a cost evaluation. In many cases, cost increase ratio is associated with improvement of the ironmaking process, and especially, the cost increment is closely related to changes in burden material quality to secure stable operation. Since there are many unknowns on improvement of burden quality at present, only the cost increment for purchased energy was considered here. The cost of steel scrap at the furnace was also assumed to be zero. As can be understood from Fig. 13, improvement in shaft efficiency and reduction of the equilibrium temperature will result in a large cost increase due to the reduction in energy supplied to downstream processes at higher blast furnace gas utilization ratios. In contrast to this, reducing heat loss from the furnace will have relatively little influence on cost. Waste plastic injection will make it possible to achieve both a CO₂ reduction and cost reduction by reducing consumption of fossil fuels. Charging of steel scrap as iron resources has a large CO₂ reduction effect, however the evaluation naturally differs greatly depending on the price of these steel scrap sources. Therefore, an economical iron source supply is indispensable.

Next, the energy saving effect in downstream processes and types of supplied energy were studied. The results of a calculation using Natural Gas to compensate for the above-mentioned shortage of supplied energy in the works are shown in Fig. 14. Needless to say, Natural Gas is extremely disadvantageous from the viewpoint of cost, however Natural Gas has a CO₂ reduction effect due to its high hydrogen content. Although improvement in the thermal efficiency of combustion furnaces is not considered here, use of high-calorie hydrogen-based energy in downstream processes seems meaningful. The case of implementing a 10% energy saving in the downstream processes is also shown, and substantially reduces the cost increment. Thus, simultaneously with low RAR operation, energy saving countermeasures for downstream processes are also extremely important.

6. Direction of Blast Furnace Operation of Japan in Future

Figure 15 shows the relationship among RAR, coke rate and reducing agent injection rate. The actual states of main

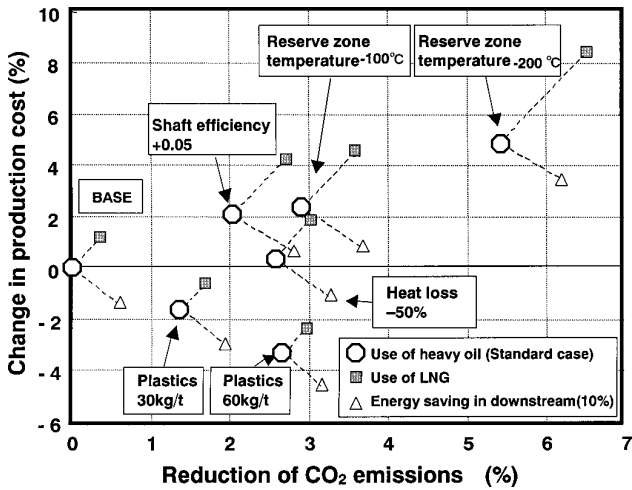


Fig. 14. Estimation of change in production cost and reduction of CO₂ emissions by use of LNG and energy saving in downstream.

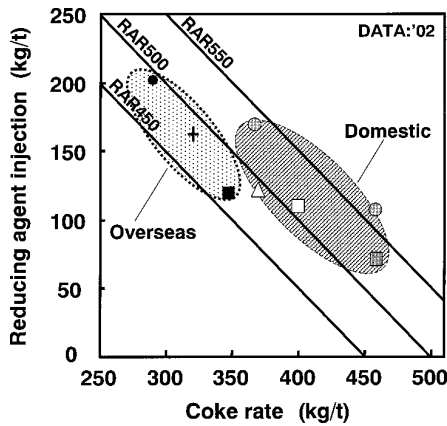


Fig. 15. Relationship among RAR, CR and reducing agent injection.

blast furnaces in Japan and other countries are also shown in Fig. 15. While also depending on energy conditions in the individual steel works, Japanese steel works assign high priority to the gas supply function of the blast furnace due to the high energy cost in Japan. From this reason, until now, there was a direction towards relatively high RAR operation in comparison with blast furnaces in foreign countries. Moreover, Japanese mills also attach importance to high ratio use of inexpensive raw materials. However, from the viewpoints of global warming problem and shortage of coke supply, from now on Japanese steel works should move toward low RAR operation, keeping raw materials conditions as mentioned above. Then, surplus heat capacity of blast furnace will be smaller in comparison with conventional operation, and it will be necessary to achieve stable operation under severe operating conditions. It must be recognized that RAR of blast furnace should be reduced in such a limited conditions to fulfill energy balance in integrated steel works. Figure 16 shows the relationships between productivity and RAR.⁴⁾ Even in Japan, in parallel with low RAR operation, high productivity operation will be selected due to high steel production demand. Figure 17 shows the relationships between RAR and coke strength in Japan and foreign countries.⁴⁾ Overseas blast furnace secures low RAR operation by using high quality burden ma-

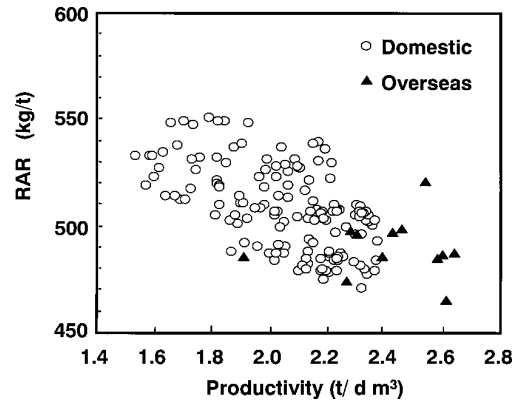


Fig. 16. Relationship between RAR and productivity.

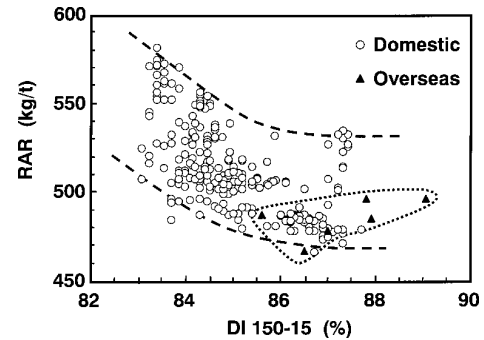


Fig. 17. Relationship between RAR and coke strength.

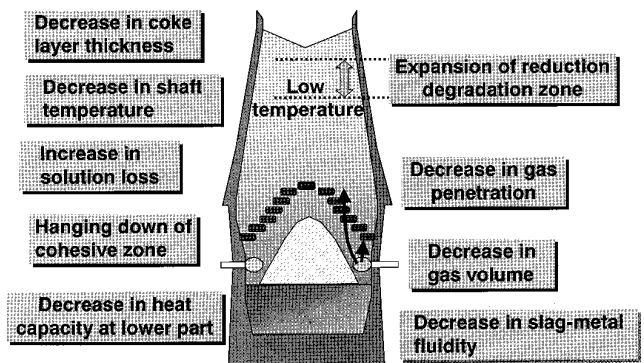


Fig. 18. In-furnace phenomena under low reducing agent rate operation.

terials. However, Japanese blast furnace should attain low RAR operation with current burden quality condition to keep competitive position, and regarding this point a newly designed technology scheme is required.

7. In-furnace Phenomena in Blast Furnace under Low RAR Operation

In-furnace phenomena estimated under low RAR operation can be shown in Fig. 18. Due to decrease in coke layer thickness, relative increase in solution loss reaction rate to specific coke and increase in residence time of coke, coke degradation in blast furnace is accelerated. Furthermore, it is considered that pressure drop in the lower part increases due to the lowering of cohesive zone level. Because the specific gas volume decreases, the penetration force of gas into the center tends to decline. Then, gas flow in the lower part

shows a strong tendency to shift to peripheral flow, causing intensified heat-loss, and shaft efficiency becomes worse. Regarding upper part of the blast furnace, due to increase in heat flow ratio, burden temperature decreases, and reduction degradation and stagnation of burden are observed. In the case of high productivity operation that is another important issue in ironmaking besides low RAR operation, reduction stagnation and increase in pressure drop will be clearly notified.^{5,6)} It is assumed that fluidization of coke, instability of burden descending and flooding of slag in the lower part occur frequently. As a whole, blast furnace operation is affected by a slight change in burden qualities and operation factors, and improved control technology is required to secure stable blast furnace operation under low RAR.

Among the change in in-furnace phenomena, a remarkable matter is accumulation of coke fines. **Figure 19** shows the relationship between coke fine ratio and pulverized coal injection rate (PCR). During high PCR operation, the increase in coke residence time and physical changes in raceway have a great influence on coke degradation.^{7,8)} Basically, the amount of fines increases remarkably when PCR is increased.^{9,10)} It is estimated that the similar phenomena appears in low RAR operation. Accordingly, when low RAR operation is adopted, coke fine ratio in deadman increases, especially in the intermediate and central part of the lower part.¹¹⁾ **Figure 20** shows the relationship between the operation index in actual blast furnace such as pressure fluctuation, burden descending and fine coke ratio in deadman.¹²⁾ Through accumulation of coke fines, unstable gas

flow, pressure fluctuation and burden descending irregularity can be frequently observed.

Consequently, it is assumed that the remarkable change occurs in the lower part of blast furnace under low RAR operation. The lower part phenomena estimated from the past researches can be represented in **Fig. 21**. When coke fines generated in the raceway accumulate in large quantity in the lower part, particularly in the deadman, gas permeability deteriorates in the direction of the deadman. Moreover,

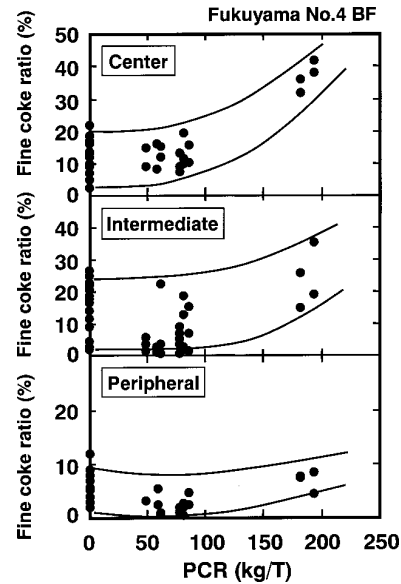


Fig. 19. Influence of PCR on fine coke ratio in deadman.¹¹⁾

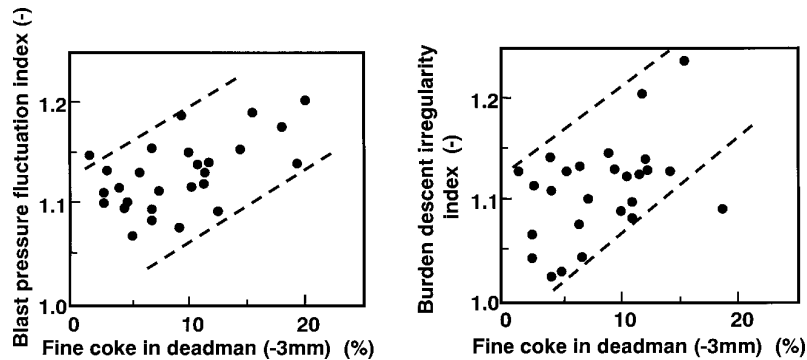


Fig. 20. Influence of fine coke ratio in deadman on operation index.¹²⁾

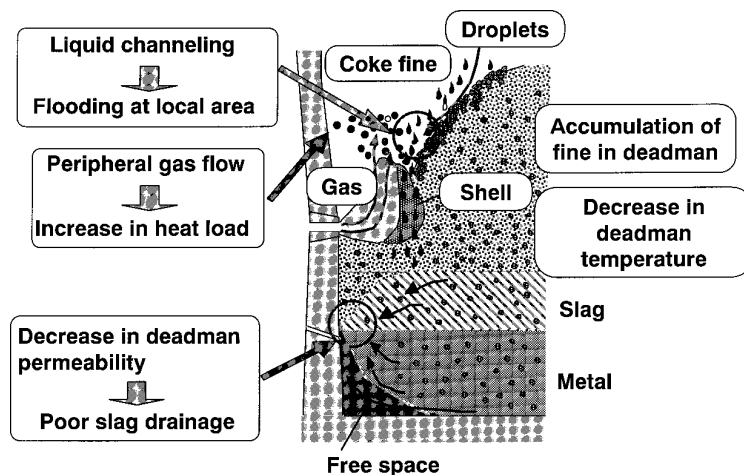


Fig. 21. Estimated lower part phenomena under low reducing agent rate operation.

raceway shell is formed in the depth of the raceway. Following these phenomena, penetration of the reducing gas generated in the raceway into the deadman decreases, strongly intensifying a shift to peripheral gas flow, and simultaneously the temperature of the deadman decreases. When the deadman permeability is small and a temperature drop occurs in the deadman due to insufficient heat supply, both slag viscosity and liquid flow resistance increase, and as a result, slag drops do not penetrate into the deadman.¹³⁻¹⁵⁾ Dropping molten iron and slag concentrate in an extremely narrow region nearby the end of the raceway. Then the channeling of liquid causes flooding phenomena of slag, and pressure drop in the lower part increases. It is estimated that the phenomena observed in actual blast furnace shown in Fig. 20 resulted from these phenomena. By clarifying and solving these subjects based on basic researches, the stable RAR operation can be attained. Finally, the results of these researches lead to reduction of CO₂ emissions from steel works.

8. Conclusion

Reduction of CO₂ emissions by the Japanese steel industry requires efforts from various angles, taking advantage of the industry's technological capabilities. The basic direction for integrated steel works in the future will be low RAR operation of blast furnaces, however this must be preconditioned on measures which consider the balance of energy supplied to downstream processes. In the ironmaking processes, the reduction of heat-loss in the lower part of blast furnace and the improvement of shaft efficiency are effective for reducing CO₂. While the basis for CO₂ reductions will be identification of the most appropriate points for CO₂ reduction in the entire system in combination with cost evaluation, further energy savings in downstream processes will also be important. Use of waste plastic, biomass and other resources derived from wastes are worth positive considering.

In low RAR operation, in-furnace phenomena, especially in the lower part, shows remarkable changes. Coke degradation will be serious in such a condition, then phenomenon to which special attention should be paid is accumulation of coke fines in the lower part. Peripheral gas flow is intensified and heat-loss in the lower part increases due to low permeability in the deadman. It is assumed that burden descending becomes instable and flooding of slag the lower part occurs. To attain stable low RAR operation, these subjects must be clarified and solved, and new control measures based on fundamental researches should be developed.

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