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Blast Furnace Ironmaking Process Using Pre-reduced Iron Ore

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Abstract

It may be possible to improve the productivity and flexibility of the blast furnace operation and also to substitute energy sources in the pig iron production processes by combining the partial reduction process using low carbon content energy sources such as natural gas with the blast furnace process. Therefore, the productivity of producing partially reduced ore, the composition of the partially reduced ore and the reducing agents rate in the blast furnace when the partially reduced ore was used were examined. It was found that this method not only reduces energy consumption in the existing blast furnace ironmaking process, but also reduces the energy consumption related to carbon dioxide emission in the total hot metal production processes, including the partial reduction process.

1. Introduction

Japan's iron and steel industry – a raw materials processing industry that consumes huge amounts of energy – accounts for some 15% of CO_2 emissions in the country, even though it has achieved a high level of efficiency. Also from the standpoint of the global environmental preservation, it is necessary for the industry to quickly take every possible measure to reduce the consumption of energy, and these measures include using alternative energy sources. In Japan, about 80 million tons of hot metal is produced annually using the blast furnace process. The energy that is used for reduction and heating in this process comes largely from coal and coke. The energy consumed in the ironmaking processes accounts for as much as about 70% of the energy that is used by the integrated steelworks. On the other hand, the by-product gas from the ironmaking process (blast furnace gas and coke oven gas) is supplied to related processes and power stations. Therefore, in order to reform the energy structure of the iron and steel industry, it is first necessary to review the raw materials and reducing agents used in blast furnaces. In addition, the industry is urged to respond effectively to the present state of iron ore resources – less high-grade lump ore and more hard-to-sinter fine ore.

Manufacturing pre-reduced ore and using it in the blast furnace is considered one of the promising technologies to be developed to dramatically improve existing ironmaking technology[1)]. Using pre-reduced ore as a raw material in the blast furnace is effective in increasing the blast furnace productivity and decreasing the reducing agents rate[2)]. Fine ore is a raw material for sinter that is the main component of the blast furnace burden. There are, however, fine ores that contain considerable amounts of combined water and alumina and hence are hard to sinter. It is thought that even those fine ores will become easily usable in the blast furnace process if they are pre-reduced to eliminate the need for processing by the sintering machine. Therefore, there has been research on and development of technologies for injecting pre-reduced fine ore into the blast furnace through the tuyere[3-6)].

By using pre-reduced ore in the blast furnace, it is possible to decrease the reducing agents rate in the existing blast furnace process and thereby save energy. In this case, however, it is important to study whether or not significant saving of energy can be achieved when considering the entire hot metal production process, including

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the pre-reduced ore production process. Namely, it is necessary to discuss not only the change in reducing agents rate in the blast furnace process but also the energy required to produce the pre-reduced ore, to transport the iron ore by sea, and to produce coke and sinter, etc. in order to determine the possibility of saving energy in the integrated ironmaking process. It is thought that using natural gas to produce the pre-reduce ore will help reduce the emission of CO_2 from the blast furnace process since it has the effect of substituting natural gas for part of the coal used in the process, although this favorable effect has yet to be evaluated quantitatively.

Therefore, concerning the use of pre-reduced ore in the blast furnace process, a comprehensive study was undertaken to cover the following: the productivity in manufacturing of pre-reduced ore, the composition of pre-reduced ore, the changes in reducing agents rate and productivity when pre-reduced ore is used in the blast furnace, the change in condition of the furnace hearth due to injection of pre-reduced ore from the tuyere, the limitations on injection of pre-reduced ore, the total amount of energy required for production of hot metal, and the change in unit carbon consumption.

2. Configuration and Aim of Two-Stage Ore Reduction System

The blast furnace ironmaking system using pre-reduced ore (“two-stage reduction system”) is a two-stage ore reduction system that consists of a process for pre-reducing iron ore by using natural gas or some other suitable energy containing a comparatively small amount of carbon and a blast furnace process for further reducing and melting the pre-reduced iron ore. This system aims to save energy and use alternative energy sources in the hot metal manufacturing process and to improve the productivity and flexibility of blast furnace operations. The concept of the system is shown in **Fig. 1**.

1) Pre-reduction process

This process produces pre-reduced iron ore by reducing raw iron ore using reformed natural gas consisting mainly of hydrogen and carbon monoxide. In order to secure high productivity of the process, the degree of ore reduction in this process is limited to a degree where there is no visible decline in the reaction speed as the reduction progresses (the reduction degree is kept within about 80%). A fluidized bed is used when reducing fine iron ore directly[5-7], whereas a shaft furnace is used when reducing lump ore or pellets.

2) Final reduction & melting process

When pre-reduced fine ore is to be used in an existing blast furnace, the tuyere of the furnace is enabled to inject the pre-reduced fine ore into the furnace. When the pre-reduced ore is in the form of a lump, it is fed into the furnace from the top. In either case, the pre-reduced iron ore undergoes final reduction using a coal-based energy to obtain hot metal.

The following are the advantages of the two-stage reduction system:

(1) In the pre-reduction process, a high degree of ore reduction near the end point of the reaction is sacrificed for the sake of a high reaction rate. This helps increase the productivity of the process and reduce energy loss.
(2) Since the raw iron ore is reduced only partially, sticking or clustering hardly occurs in the pre-reduced ore production process. This improves operational performance.
(3) An existing blast furnace can directly be used for the final reduction and melting process. This helps reduce the investment in equipment and the process development risk.
(4) Thanks to the pre-reduction of iron ore, it is possible to reduce the unit consumption of energy in the blast furnace system that uses coal-based energy. It is also possible to reduce the generation of carbon dioxide. In addition, since the reduction load is decreased, the blast furnace productivity increases.
(5) When the pre-reduction process is located near iron ore mining site, it is possible to save the energy required to transport the oxygen and combined water removed from the ore during pre-reduction. Since the coke rate decreases, it is also possible to reduce the energy required to transport the coking coal.
(6) By using low-grade iron ore that is unsuitable for sinter for the pre-reduction process, more low-grade iron ore is used for blast furnace process. This also makes it possible to maintain the quality of iron ore used for sinter and improves the properties of sinter.
(7) The practice of blowing natural gas directly into the blast furnace is not uncommon overseas. In Japan, however, it can hardly be justified economically because natural gas is comparatively costly. If the pre-reduction of iron ore is carried out in a foreign country in which natural gas is available at low cost, it might become economically possible to switch to alternative energy sources.

Furthermore, if pre-reduced ore becomes widespread, it might become possible to replace the conventional blast furnace with a new reduction and melting furnace (e.g., smelting reduction process) that uses pre-reduced ore as a raw material for hot metal. Thus, the stage

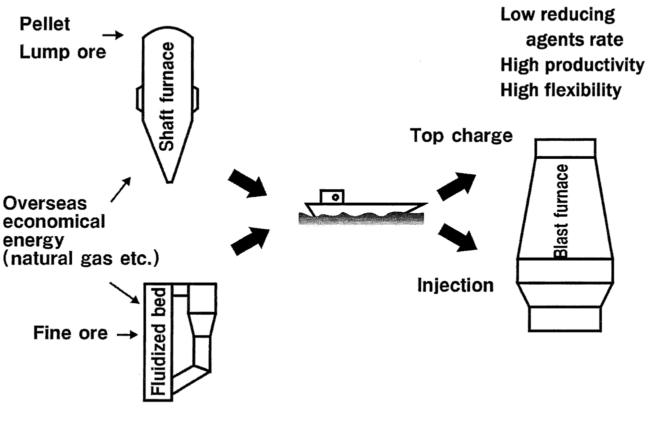

Fig. 1 Process image of two stages reduction system

may be set for a new process that is smaller in scale and higher in flexibility than the blast furnace.

3. Study of Component Technologies

By using pre-reduced ore in the blast furnace, it is possible to save energy in the conventional blast furnace ironmaking process. However, it is necessary to discuss whether or not significant savings of energy can be achieved when consideration is given to the entire hot metal production process, including the pre-reduced ore production process. Namely, it is necessary to study not only the change in blast furnace reducing agents rate but also the energy required for production of pre-reduced ore, transportation of the ore by sea, production of coke and sinter, etc. in order to determine the possibility of reducing the total amount of energy required for the production of hot metal.

To that end, it is first necessary to understand how the productivity of the pre-reduced ore production process changes according to the degree of pre-reduction and how the coke rate, productivity, etc. of the blast furnace changes when pre-reduced ore is used in the blast furnace. Using natural gas for pre-reduction can help reduce the emission of carbon dioxide from the blast furnace process since natural gas is substituted for the coal used in the process. Therefore, a study was conducted to understand the effect of using natural gas has on reducing carbon dioxide emissions.

3.1 Manufacturing of pre-reduced ore

The metallization degree of conventional direct reduced iron is about 90 to 95%. This represents the grade necessary for scrap iron used in an electric furnace. When the metallization degree of reduced iron used in an electric furnace is low, much of the heat applied is used to reduce the residual FeO and hence the unit electricity consumption increases. Because of this, direct reduced iron is required to have a considerably high metallization degree. On the other hand, with the blast furnace, which in principle is capable of reducing iron oxide, there is no problem of residual iron oxide. Generally speaking, the higher the reaction degree (metallization degree), the sharper the decline in reaction speed. Therefore, when a high metallization degree is required, as in the case of direct reduced iron used in an electric furnace, the production speed must be lowered much more than when low metallization suffices. Besides, the fixed cost becomes relatively more burdensome. Therefore, a study on the relationship between degree of reduction and productivity was undertaken.

The process characteristics of fine ore reduction by a fluidized bed were obtained from a circulating fluidized bed pilot plant[6]. The riser – the reaction region of the pilot plant – have an inside diameter of 550 mm, is 10 m in height, and the overall height of the plant is about 25 m.

An example of the relationship between ore feed rate and degree of reduction is shown in **Fig. 2**. When the ore feed rate is increased from 0.5 to 1.0 t/h, the degree of reduction decreases from 90 to 60%. Thus, the degree of reduction of the ore decreases with the increase in ore feed rate. Since the above results include the influences of temperature of the riser and particle hold-up, we examined those influences using reaction models. The reaction model used was a single-interface un-reacted core model with chemical reaction as the rate-determining factor. The residence time distribution was evaluated by using a perfect mixing model. An example of the relationship between reduction time and degree of reduction, calculated by using this model, is shown in **Fig. 3**. By using such a reaction model, it is possible to estimate the relationship between changes in average residence time and reduction temperature, caused by an increase or decrease in feed rate, and the degree of reduction. According to Fig. 3, the reduction time required to secure a 90% degree of reduction at the reduction temperature of 880℃ is about 120 minutes, whereas the reduction time required to secure a 60% degree of reduction at the same temperature is about 20 minutes. Namely, the productivity with a 60% degree of reduction is about six times higher than that with 90% degree of reduction.

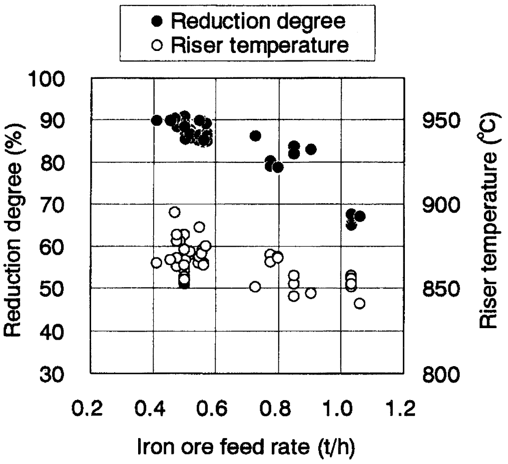

Fig. 2 Influence of iron ore feed rate on reduction degree and temperature

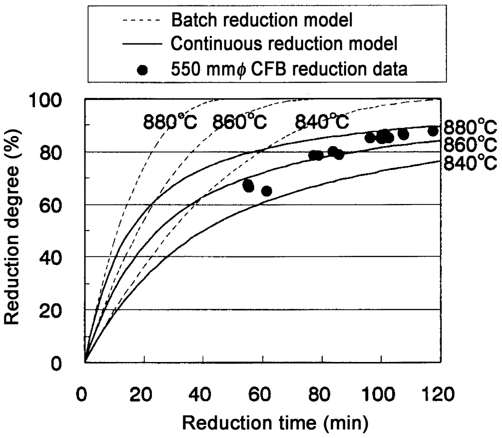

Fig. 3 Calculation results on relation between residence time and reduction degree

Fig. 4 shows the iron composition of pre-reduced ore reduced by a one-stage perfect mixing fluidized bed and is based on experimental results[7]. Given the same degree of reduction, the continuous reduction process results in a smaller amount of Fe^{2+} and a slightly larger amount of metallic iron (M.Fe) than the batch reduction process.

Also in the case of a shaft furnace, the productivity changes sharply as the ore metallization degree is varied. According to **Fig. 5**, which is based on data obtained from an commercial shaft furnace[8], the metallization degree of ore is determined by reduction temperature and production rate. At a given temperature, the reduction speed increases markedly when the metallization degree is lowered. For example, at a reduction temperature of 1,040K, even when the reduction speed is increased 36%, from 1,400 t/d to 1,900 t/d, the met-

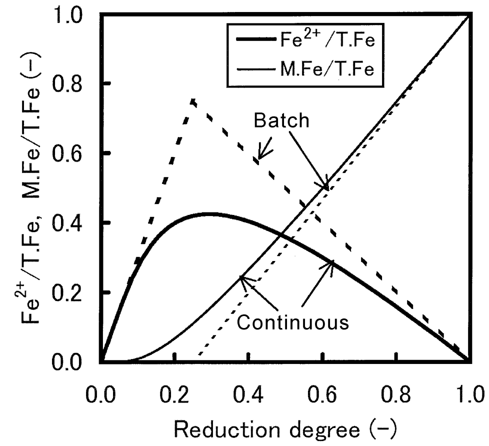

Fig. 4 Calculated relationship between reduction degree and iron composition

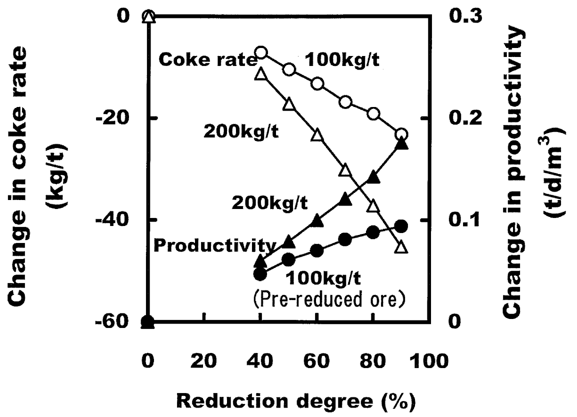

Fig. 6 Effect of reduction degree of charged pre-reduced ore on coke rate and productivity of blast furnace

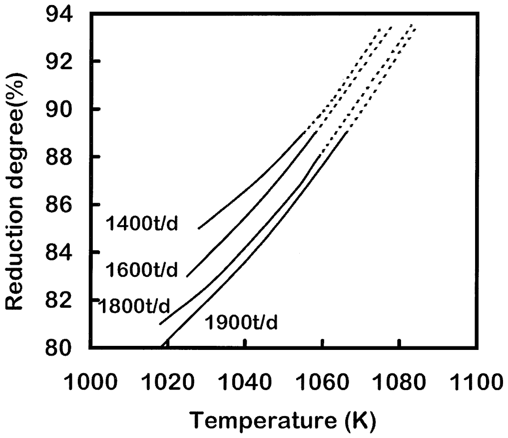

Fig. 5 Relation among reduction temperature, reduction degree and production rate of shaft furnace

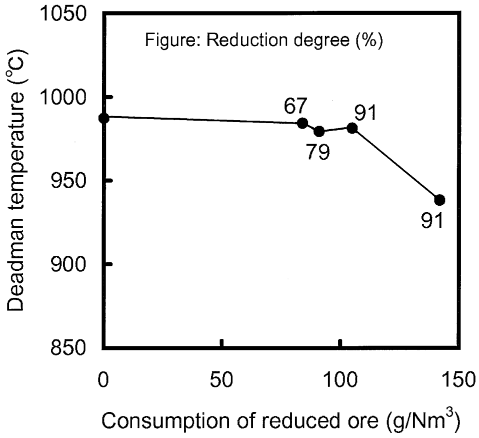

Fig. 7 Relation between pre-reduced ore injection rate and deadman temperature

allization degree decreases only about three percentage points, from 87 to 84%. Thus, reducing the metallization degree of ore makes a substantial contribution to the improvement in reduced-iron productivity.

Generally speaking, when iron ore is reduced by a fluidized bed or shaft furnace, there is concern that sticking or clustering of reduced ore might occur in the reactor. In the two-stage reduction system, by contrast, sticking or clustering can hardly occur since the iron ore is only partially reduced. This facilitates the ore reduction operation.

3.2 Use of pre-reduced ore in blast furnace

The effects of feeding pre-reduced ore into a blast furnace at a rate of 100 and 200 kg/t-p were studied, respectively. Although point W and furnace-top O/Fe in the Rist diagram shifted according to the amount of metallic iron in the ore, the marginal decline in coke rate was calculated assuming that the shaft efficiency and pulverized coal rate remained unchanged. As shown in **Fig. 6**, when the degree of reduction of pre-reduced ore is higher than 30%, at which metallic iron begins to be produced, the coke rate decreases linearly as the degree of reduction is increased. While in the blast furnace, there is an almost linear relationship between coke rate and degree of reduction, the production rate in the reduced ore production process sharply increases as the degree in reduction decreases, as already mentioned. Therefore, there is likely an optimum combination of pre-reduced ore and blast furnace operation. In addition, even when pre-reduced ore is used, it is possible to increase the blast furnace productivity without changing the blast volume, just like when direct reduced iron is used[9)].

A blast furnace simulator[10)] was employed to study the change in conditions of the lower part of the blast furnace when pre-reduced ore is injected into the furnace through the tuyere. This simulator is a sector model furnace (center angle: 90 degrees) provided with one tuyere. The hearth radius is 600 mm and the charging level from the tuyere level is 2,000 mm. **Fig. 7** shows the change in deadman temperature when pre-reduced ore was injected into the furnace with the pulverized coal injection rate kept constant at 200 g/Nm^3.

Even when pre-reduced ore was injected into the furnace, the deadman temperature remained almost the same. However, when fine ore with a 91% degree of reduction was injected at a rate of 142 g/Nm^3, the deadman temperature declined markedly. In this case, too, the reducing agents rate and other conditions had been set so as to fulfill the total heat balance, and the flame temperature at the tuyere front remained the same. However, the local heat-flax ratio in the lower part of the furnace increased with the rise in oxygen enrichment ratio. This suggests the possibility that the deadman temperature might have dropped due to a decline in the ability to heat and reduce the material fed from the furnace top. Naturally, the marginal ore injection rate depends on some other factors as well. Even so, it is considered desirable that the injection rate should be about 140 g/Nm^3 or less. Thus, when it comes to injecting pre-reduced ore into the furnace through the tuyere, there are certain limitations in terms of thermal conditions and the marginal injection rate. It is thought, however, that there are less strict limitations on pre-reduced ore than unreduced ore.

4. Evaluation of Energy Consumption

The following case was calculated to study the resulting changes in unit energy consumption and unit carbon consumption[11]; West Australian fine ore of pisolite – a raw material for sinter containing a considerable amount of combined water and alumina – was pre-reduced to 60% by a circulating fluidized bed using reformed natural gas on the spot and injected into a blast furnace at a rate of 130 kg/t. By transporting to Japan pre-reduced ore produced overseas using inexpensive energy and using it in blast furnaces in the country, it will become possible to decrease the coke rate and reduce the energy required for the production of coke. In addition, the energy required for production of sinter will decrease as the sinter ratio can be lowered. When ore is pre-reduced, the combined water and oxygen it contains are partly removed. This makes it possible to save part of the energy required to transport the ore by sea to Japan. Furthermore, the decrease in coke rate makes it possible to reduce the energy required to transport coal.

For the ore pre-reduction process, a two-stage fluidized bed process consisting of a preheating fluidized bed and a reducing fluidized bed was employed. For the reducing gas, a mixture of natural gas partially burned in oxygen and preheated circulating gas obtained from exhaust gas by removing carbon dioxide and water was used.

Fig. 8 shows the unit energy consumption required to produce pre-reduced ore. The primary energy consists mainly of natural gas in the reducing gas production process. This natural gas is also used to preheat the ore and circulating gas, and as the primary energy for production of oxygen and the generation of electricity. It was found that producing one ton of pre-reduced ore with a 60% degree of reduction requires 7.26 GJ of energy and 118 kg of carbon.

Table 1 shows the calculated results about the ironmaking process using pre-reduced ore. When pre-reduced ore with a 60% degree of reduction is used in a blast furnace at a rate of 130 kg/t-p, the coke rate decreases from 370 to 352 kg/t-p and the unit sinter consumption decreases from 1,211 to 1,042 kg/t-p, with the pulverized coal rate remaining constant. As the coke rate and unit sinter consumption decrease, the consumptions of coal and fuel for coke production and the consumption of coke, anthracite and electricity in the sintering machine decrease.

As a result, the unit energy consumption in the existing ironmaking process decreases by 0.97 GJ/t-p, or approximately 6%, from 17.02 to 16.05 GJ/t-p (**Fig. 9**). Taking into account the energy required for production of pre-reduced ore (0.94 GJ/t-p) and the

Table 1 Estimated consumption of ironmaking processes when partially reduced ore is used

		Base	Pre-reduced ore
Blast furnace			
Coke rate	kg / t-pig	370	352
Pulverized coal rate	kg / t-pig	145	145
Pre-reduced ore	kg / t-pig	0	130
Sinter	kg / t-pig	1211	1042
Other ore	kg / t-pig	404	404
Blast volume	Nm^3/ t-pig	982	936
Oxygen	Nm^3/ t-pig	37	38
Electric power	kWh / t-pig	32	32
Coke oven			
Coal	kg / t-pig	585	556
Fuel	Mcal / t-pig	332	310
Electric power	kWh / t-pig	20	19
Steam	kg / t-pig	20	19
Sintering plant			
Ore	kg / t-pig	1258	1082
Fine coke	kg / t-pig	39	31
Anthracite	kg / t-pig	21	18
Electric power	kWh / t-pig	42	36
COG	Nm^3/ t-pig	2	2

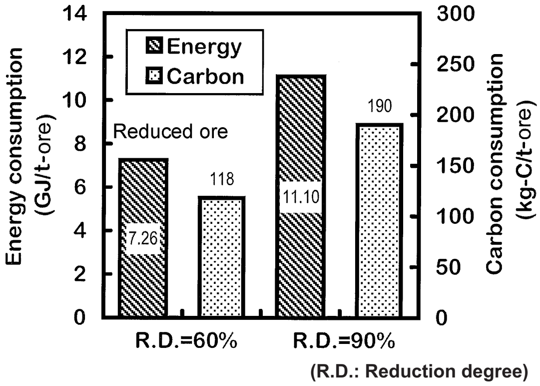

Fig. 8 Energy consumption and carbon consumption required to produce partially reduced ore

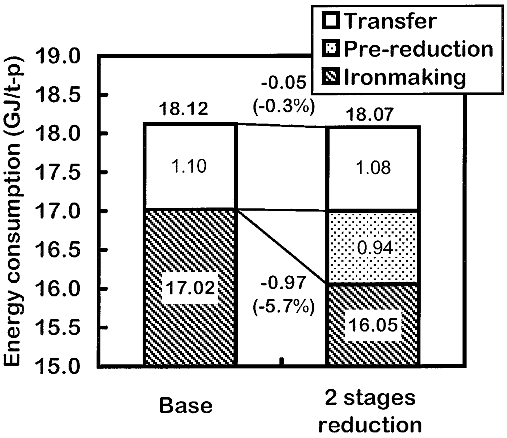

Fig. 9 Comparison of energy consumption under the base conditions and for the two-stage reduction system

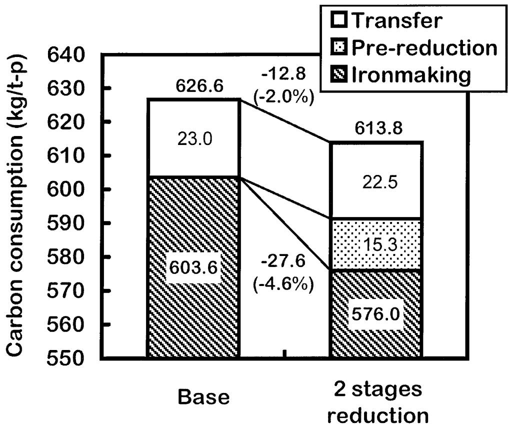

Fig. 10 Comparison of carbon consumption under the base conditions and for the two-stage reduction system

decrease in consumption of energy required to transport the ore by sea (0.02 GJ/k-p), the decrease in total unit energy consumption comes to 0.05 GJ/t-p, or approximately 0.3%.

Similarly, the unit carbon consumption in the existing ironmaking process decreases by 28 kg-C/t-p, or about 5%, from 604 to 576 kg-C/t-p (**Fig. 10**). Taking into account the unit carbon consumption for production of pre-reduced ore (15.3 kg-C/t-p) and the decrease in unit carbon consumption to transport the ore by sea (0.5 kg-C/t-p), the decrease in total unit carbon consumption comes to 12.8 kg-C/t-p, or approximately 2%.

5. Conclusion

A two-stage ore pre-reduction system was studied that combines a process for pre-reducing ore by using natural gas or some other suitable energy source containing a comparatively small amount of carbon and a blast furnace process for performing the final reduction and melting of the pre-reduced ore, with the aim of being able to switch to some suitable alternative energy source for the hot metal production process and improving the blast furnace productivity and flexibility. As a result, the following conclusions were made.

(1) By avoiding a high degree of reduction in the reduced ore production process, that is, by reducing the ore only partially to ensure a high reduction speed, it might become possible to improve the productivity and decrease the production cost per unit of metallic iron even with a single-stage fluidized bed reduction process.

(2) With respect to the use of pre-reduced ore in a blast furnace, injecting pre-reduced ore into the furnace at a high rate can cause the deadman temperature to decline. However, as long as the injection rate is kept within a certain range, it should be possible to lower the reducing agents rate, increase the blast furnace productivity, and improve the permeability in the lower part of the furnace.

(3) It is thought that the two-stage ore pre-reduction system will make it possible not only to save energy in the conventional blast furnace process but also to reduce the total consumption of energy and the total emission of carbon dioxide in the entire hot metal production process, including the pre-reduced ore production process.

In order to implement an industrially viable two-stage reduction system that helps decrease the ore reduction operation's dependence on coal-based energy, it is important not only to develop the technology for producing and using pre-reduced ore, but also to make sure that the system permits the manufacture and use of considerable volumes of pre-reduced ore on a commercial basis. To that end, there are a number of tasks that remain to be tackled in the future, including evaluation of pre-reduced ore production, storage and application technologies, assessment of energy required for hot metal production, process design, and feasibility study of the total system. Nevertheless, for Japan, it is thought that has limited natural resources, the promotion of the international division of labor, utilization of the most favorable energy sources available overseas, and development of an innovative new ironmaking process that makes the most effective use of the existing equipment and infrastructure are important and solvable issues.

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