Recent Progress and Future Prospects in Blast Furnace Fuel Injection in Japan

By Heiji IKEGAMI**

I. Introduction

The recent revolution in energy sources for industrial purposes is seriously affecting the steel industry, and particularly urging technical innovations in blast-furnace-ironmaking technologies, because the blast furnace consumes much energy. Strike by American mine laborers from the middle 1969 through 1970 have led to the supply shortage of metallurgical coal. This has made feel anxiety about the future of the energy sources for the Japanese steel industry. Apart from Australian and Canadian mines which will be developed in the future and become important sources of supply, Japanese industry cannot be optimistic about the supply of low volatile coking coal, in view of the labor conditions abroad, growth of the EC steel industry, and the retarded development of the Japanese steel industry. Demand for coal has slightly decreased in the period from the end of 1970 to 1971, under the influence of the arrival of coal to cover emergency orders and the market slump for steel caused by economic depression. In view of the price increase, however, the shortage of low volatile coal would continue in the long run.1)

Among conceivable counter-measures, the most important is the development of coal resources, which can be made in the coal-producing countries. So far as the blast furnace ironmaking should be continued, furthermore, the most important research would be the development of production processes of coke capable of bearing the blast furnace process even with a low blending ratio of low volatile coal, and technologies for lowering the coke consumption by the injection of alternative fuels. Technologies for employing alternative fuels into blast furnace have been studied by various iron producers already since the 1960’s. The Blast Furnace Fuel Injection Committee (BFI) was organized in Japan in 1962 for this purpose, and the good cooperation of all the member companies should be highly evaluated.

Price increase of crude oil imposed at the firm request of the OPEC in 1971 is considered a serious challenge to the future of the utilization of alternative fuels. The crude oil consumption in Japan is estimated to reach 600 million kl in 1980, or about three times that at present, and the demand-supply relation may seriously be impaired. As is generally claimed recently, the mankind is the crew of the spaceship called the earth but possessing limited resources. It would be a mission for us, who are engaged in the steel industry consuming much energy resources, to fully make use of diversified energies, and also to prevent the pollutions.

In only five years since the publication of a comprehensive report2) on the fuel injection techniques by the BFI Committee in 1966, circumstances around energies have completely transfigured. Now that such a revolutionary change is experienced, the publication of a “Special Issue on Combined Blast into Furnace” planned by the Iron and Steel Institute of Japan is very significant. Techniques for the effective use of diverse energies without pollution, would be the most important subjects in enhancing the fuel injection technologies in the future.

From this point of view, this paper presents the recent progress of fuel injection technologies in Japan together with a few comments on the future problem.

II. Recent Progress of Ironmaking Techniques and Contribution of Fuel Injection

As is generally known, the recent technical progress of the iron and steel production in Japan is very remarkable as a whole. Iron production increased from about 20 million t in 1963 to 67.5 million t in 1970. This is chiefly attributable to the construction of new large blast furnaces: as shown in Fig. 1, an average iron production per blast furnace of 3 100 t/day was recorded in 1970.3) The productivity has also increased almost linearly as shown in Fig. 2, up to a level of 1.95 t/m²/D in average.4) These parameters

![Graph](image-url)

Fig. 1. Trend of average pig iron production per unit of blast furnace in Japan

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would suggest the excellent progress made in operating practices.

Coke rate has sharply decreased, as shown in Fig. 3, with the increase in the amount of the injected fuel since 1961: approximate figures include an amount of injected oil of 40 kg/tHM,$^2$ and a coke rate of 520 kg/tHM in average. The coke rate has still decreased gradually to reach almost a constant level of 500 kg/tHM in 1965, and the oil rate has rather tended to decrease. The cause of this fact is not as yet perfectly clear, but the following factors should have assisted this tendency at least to some extent:

1) Emphasis placed on the high production rate necessarily required to lower the oil rate for ensuring a sufficient permeability through the furnace burden.

2) In the inability of injecting oil caused by an unexpected accident during large quantity oil injection, the furnace chill, and moreover, the furnace condition is impaired; especially in an accident of water leakage from tuyere and cooler into the furnace hearth, the amount of injection was limited to ensure a safety.

3) Heat compensation was conducted by increase of the blast temperature to keep a necessary flame temperature at tuyeres. After the blast temperature reached its upper limit and additional moisture cut-down, the heat compensation is not possible for the fuel injection.

With a view to using much more alternative fuels over these limits, theoretical analyses and research were made to minimize accidents through countermeasures taken against tuyere breakage and preventive maintenance. In 1970, a technique for injecting fuel in a large quantity was adopted with the simultaneous use of oxygen enrichment so far attracting no attention in the past due to its price, because of shortage and price increase of coking coals, as written above, and this considerably reduced the coke rate. As compared with 1965, the coke rate decreased by about 20 kg/tHM in 1970, and the amount of injected oil increased by 15 kg/tHM from 29 to 44 kg/tHM.

Oxygen for BOF has been used in blast furnaces, as shown for BOF in Fig. 4, in an amount of 11 m$^3$/tHM in national average in 1969, which has gradually increased through 1970 up to 25.8 Nm$^3$/tHM (1.7% enrichment) in average in May 1971. Many blast furnaces are having own oxygen plants. Amount of injected oil has also increased to 58 kg/tHM, and the coke rate has decreased 447 kg/tHM.

Heavy oil is the main fuel injected for this purpose, whereas it is increasingly becoming the usual practice to inject tar. Coke oven gas is injected at the Yawata Works$^5$ and Nippon Kokan.$^6$ At the Muroran Works, the injection of natural gas is considered, which is not as yet in use at present in spite of its sufficient adaptability. Injection of coke oven gas separated by low temperature processing seems to be under test. It was reported that naphtha was trially injected at the Hirohata Works in 1963 and proved the possibility of injection.$^5$ Muroran injected slurry consisting of oil and coal, taking advantage of its geographical conditions,$^6$ and Kawasaki Steel's Chiba Works carried out a slurry injection experiment, which was however discontinued.$^7$ Experiments conducted on the injection of fuels other than oil are indicated in Table 1. From the point of view of effectively utilizing diversified energies, the injection of crude oil, naphtha, LPG and LNG have been studied. Large quantity injection of oil, as applied at present, such as 70 to 100 kg/tHM
requires the injection of low sulphur oil to limit the sulphur content in pig, and also for preventing pollution. Supply of low sulphur oil is however estimated to become difficult, and the industrialization of injecting techniques of such low sulfur fuels will be an important subject of research in the future.

III. Progress of Theoretical Research on Composite Blasts

Oil was actually injected into a blast furnace for the first time in Japan in 1961, the operation being theoretically based on Ramm's concept of the USSR, but the actual operation rather went ahead of the theory at that time. Steady advancement has been made in theoretical research: some conclusions were reached with regard to the limit and replacement of injected oil and enhanced further development of this technology, in combination with the existing injection practice based on experience. Principal theoretical papers on the fuel injection released in recent issues of "Tetsu-to-Hagané" are listed in Table 2.

1. Limit of Fuel Injection through Tuyere

In injecting fuel through the tuyere, theoretical and practical restricting conditions of the quantity of injected fuel are as follows:

(1) Upper and lower limits of flame temperature at tuyere
(2) Excess oxygen ratio and occurrence of soot
(3) State of reduction of ore and limits of top pressure and permeability
(4) Restrictions in facilities and operations.

According to the results estimated by the BFI Committee, an injection of up to the order of 100 kg/tHM would be possible, only if appropriate measures were taken, including improved heat compensation, better permeability in the furnace, more efficient atomization, counter-measures against troubles in facilities and operations in injecting in a large quantity. Already in 1962, in Nishijima No. 1 BF, the coke rate was lowered to 367 kg/tHM by injecting oil at a rate of 153 kg/tHM, at a blast temperature of 1050°C and an oxygen enrichment of 6%.

The limit imposed by the heat compensation given above in (1) varies with the blast temperature and the blast humidity. This range is considered to be wider than that of several years ago due to the increase of about 200°C in the blast temperature for blast furnace from about 1000°C up to about 1200°C, and to the decrease in the blast humidity. Review based on Ramm's formula indicates the necessity of raising the blast temperature by 40°C for injecting oil of 10 kg/tHM. The increase in blast temperature of 200°C should therefore permit increase in injected oil of 50 kg/tHM. Figure 5 represents the results of investigation on the limits of blast temperature and injected oil, in Nippon Kokan's Kawasaki No. 4 BF. These results suggested a lower limit of 2000°C and an upper limit of 2200°C of the theoretical flame tem-

Table 1. Experimental injection of alternative fuel except oil and tar tested and proposed

<table>
<thead>
<tr>
<th>Kinds of fuels</th>
<th>Name of the company</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coke oven gas</td>
<td>Yawata 1961 Higashida</td>
<td>15% production increased and 1.8% coke rate decreased for every 1% of COG</td>
</tr>
<tr>
<td>Rest gas</td>
<td>NKK 1961 Kawasaki</td>
<td>Under testing</td>
</tr>
<tr>
<td>Naphtha</td>
<td>Fujin Steel 1963 Hirohata</td>
<td></td>
</tr>
<tr>
<td>LPG</td>
<td>Kawasaki Steel</td>
<td>Under planning</td>
</tr>
<tr>
<td>Coal slurry</td>
<td>Fuji Muroran 1964 1965</td>
<td>50% coal slurry</td>
</tr>
<tr>
<td></td>
<td>Kawasaki Steel Chiba 1964</td>
<td>30% coal slurry replacement ratio 1.0</td>
</tr>
</tbody>
</table>

Table 2. Theoretical investigations of fuel injection published in recent Tetsu-to-Hagané

<table>
<thead>
<tr>
<th>Issued data</th>
<th>Title and author of the paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>54 (1968) 10, p. 13</td>
<td>Consideration on oil replacement coefficient in blast furnace operation by F. Nakatani, S. Watanabe, Y. Sunami, F. Nakamura</td>
</tr>
<tr>
<td>53 (1967) 9, p. 3-16</td>
<td>Consideration on oil replacement coefficient in blast furnace operation by F. Nakatani, Y. Sunami, F. Nakamura</td>
</tr>
<tr>
<td>51 (1966) 8, p. 199-206</td>
<td>On the theoretical equation of the coke equivalent of injected fuel and its application by M. Tate, C. Nakane, C. Kim, K. Suzuki</td>
</tr>
</tbody>
</table>

Fig. 5. Effect of the amount of injected tar on the decrease in coke rate at different hot blast temperature
perature under the conditions at that time. At a blast temperature of 800°C, the limit of injected oil should be 30 kg/tHM, whereas an injection of the order of 110 kg/tHM is possible at 1100°C, if deduced only from the aspect of heat compensation.

Under such conditions with an increased blast temperature and a decreased blast humidity, the excess oxygen ratio of (2) is rather determining the limit of injected oil. At the Tobata Works of Nippon Steel Corp. and several other works, a coke rate of less than 400 kg/tHM is being obtained by injecting oil in an amount of 80 to 100 kg/tHM through as many as possible tuyeres with the simultaneous use of oxygen enrichment. According to this experience, the excess oxygen ratio could reportedly be lowered to 1.1 to 1.2, and this level seems at present to determine the limit of oil injection. In recent blast furnaces, the improved operating practices lowers the fuel rate, and this is resulting in a smaller amount of blast per ton of pig iron and a decreased consumption of oxygen. If the excess oxygen ratio of 1.1 to 1.2 is considered as limit, the limit of oil injection is estimated to be about 110 kg/tHM, and that of tar, 90 kg/tHM. This is now a problem of combustion engineering with the tuyere as burner, and the possibility of further decreasing the excess oxygen ratio would be an important future problem. From such a point of view, the two-stage combustion process studied at the Yawata Technical Research Center, the blast atomizing combustion, and the use of oxygen atomizing burner are interesting. If reducing gas is more actively produced and injected into the lower part of the shaft, the injection of fuel in a large quantity would be possible at a time, irrespective of the restricting conditions at tuyeres. The FTG process at the Hirohata Works, Nippon Steel and the investigation in the experimental blast furnace of Nippon Kokan give typical examples. According to a report, the injection of heavy oil in an amount of about 220 kg/tHM as reducing gas permitted reduction of the coke rate by about 210 kg/tHM. This should be noted as a direction for overcoming the limit of tuyere injection.

Research has been conducted on the intensification of ore sizing and the production of strong sinter. An effective use of an extra-high pressure now permit stable operations with a large-quantity oil injection and a decreased coke rate without a marked decrease in the permeability. These also form an indispensable background which permitted utilization of large quantities of alternative fuels. In combination with the theories, such conditions as to permit stable blast furnace operations at a sufficient permeability even with a further decreased coke rate should be clarified in the future.

2. Replacement Ratio

The most important factor in considering the economic advantages of the fuel injection is the replacement ratio of coke rate in relation to the alternative fuel. In actual results, the replacement ratio largely varies between 2 and 0.6 with operating conditions. It is therefore very important to establish a theoretical relation to give the replacement ratio. In the theoretical studies on the replacement ratio so far proposed, the utilization ratios of CO and H₂ are estimated under some restricting conditions such as a constant theoretical flame temperature, or the material balance. Also the equilibrium relation and heat balance are calculated from the CO/CO₂ ratio of the top gas. The theory has been clearly developed by Tate et al. and Nakatani et al. Tate et al. have claimed that the combined efficiency of oil and the utilization ratio of hydrogen, they are the most important factors in determining the replacement ratio, were still unknown and this definitely prevented an exact estimation. Nakatani et al. have reported that a sufficient heat compensation gave the maximum replacement ratio. An insufficient heat compensation resulted in a decrease in the utilization ratio of CO and gave the minimum replacement ratio, especially when the reduction by hydrogen took over only the direct reduction before injection. In their paper, these authors proposed the following equation. From the assumption of certain values of a CO/CO₂ ratio and a utilization ratio of H₂, Eq. (i) is valid between amount of injected oil Y kg/tHM and replacement ratio R, by the heat compensation through a 100°C increase in blast temperature:

When \( Y > 12.8 \) (kg/t): \( R = 1.053 + 6.170/Y \) ......(i)

When \( Y \leq 12.8 \) (kg/t): \( R = 1.533 \)

This suggests that the replacement ratio decreases from the maximum value of 1.535 closer to 1.053 by injecting large quantity of oil. Theoretical discussion gives the following estimations of the replacement ratio of heavy oil versus coke:

(1) Use of oil will need an increase in the blast temperature and oxygen enrichment, and a decrease in the blast moisture

(2) Oil injection will cause increase in the amount of reducing gas which in turn improves the shaft efficiency and the top gas ratio

(3) Formation of soot will cause change in combustion efficiency.

These facts are combined in a complicated way. Actual replacement ratios range from 2 to 0.6, because the estimation can not cover all the factors. The replacement, when exceeding 1.2, is the product obtained by dividing with the amount of injected oil, the decrease in coke rate brought about by the increased blast temperature, decreased moisture or increased oxygen enrichment described in (1). Further increase in the amount of injected oil would cause decrease in the replacement ratio, as is clear from Eq. (1). Strictly speaking, this is the result of the increased blast temperature, decreased moisture and oxygen enrichment.

Sometimes oil is injected with the simultaneous use of oxygen enrichment as in recent operations. A higher oxygen enrichment leads to a decreased volume of gas per ton of pig iron, and hence a slower heat exchange in the shaft and decrease in reduction rate by gas. It is thus reported that, even when a decrease
in heat loss is taken into account for the increased production, the coke rate is still raised in such cases. However, because the flame temperature at tuyeres is raised, injection of oil causes increase in the volume of gas by the amount equal to that of produced H₂, and lowers the coke rate. The thermal flow ratio, which shows the degree of heat exchange in the shaft in the form of the ratio of the heat content of burden to the heat content of gas, tends thus to decrease, and thus heat exchange in the shaft will increase. Increase in the amount of reducing gas per ton of pig iron and the unchanged utilization ratio of CO and H₂ have been ascertained by experiment. The reducibility of ore by gas should therefore be raised. For all types of blast furnace, the shaft efficiency and the CO/CO₂ ratio in the top gas is improved. Also they improve the replacement ratio and lower the coke rate by more than the heat compensation.

The soot formation largely depends upon the degree of heat compensation and the excess oxygen ratio. If an effective atomizing practice can prevent the formation of soot, the replacement ratio would be increased. A quantitative discussion on this problem is however difficult. The measurement of the quantity of soot formed has been reported from the Yawata Research Center and Osaka Steel. Efforts are being made in experiments to inject oil through as many as possible tuyeres uniformly, and if possible, by controlling independently the amount of oil for each tuyere with different excess oxygen ratios. This may be a reasonable way for avoiding the soot formation.

As described above, the replacement ratio can be estimated simply from the material and heat balances. However, in order to clarify the effect of oil injection on the furnace reactions, the blast furnace process should be studied from the standpoint of heat exchange and chemical engineering, and this will also be a subject left for future research.

IV. Large Quantity of Injection of Alternative Fuel

1. Large Quantity of Injection of Oil with Simultaneous Use of Oxygen-enriched Blast

Large quantity of injection of oil with the simultaneous use of oxygen enrichment was trially conducted at Osaka Steel in 1962: in this trial injection, 135 kg/tHM of oil was injected at an oxygen enrichment ratio of 6% and reduced the coke rate to 367 kg/tHM. This process was not widely adopted at that time for economic reasons. Subsequently, in Nippon Kokan’s Tsurumi Works, replacement ratio in oil injection and utilization of CO and H₂ have been investigated at an increased oxygen enrichment ratio of 5.7% . The reports are now available also on the effect of oxygen enrichment on the furnace condition in an experiment of oxygen-enriched blast at Sumitomo Metal’s Wakayama Works, and on mathematical models and experimental results at Nagoya Works by Wakabayashi et al.

Due to the recent price increase of coke, this technique has become economically acceptable. At Nippon Steel’s Tobata, this technique was applied for large capacity blast furnaces with an oil injection of about 100 kg/tHM, and the coke rate was reduced to below 400 kg/tHM for the first time. This may be called an epoch-making record in the large-quantity injection of alternative fuel. This technique has since been adopted in works having large blast furnaces such as those of Nippon Steel, Kawasaki Steel’s Mizushima and Nippon Kokan’s Fukuyama, with the full merits in reducing the coke rate. Figure 6 represents the recent relation between the oxygen enrichment ratio and the amount of injected oil.

In injecting oil in a large quantity with oxygen enrichment, however, it is necessary to make the following improvements in operating practice:

(1) Determination of optimal oxygen-enrichment ratio and amount of injected oil
(2) Measures to prevent blast leakage and more heating of pen stocks at flange parts
(3) Intensified control against abnormality in oil injection
(4) Closer sizing of burden, maintenance of strength and improvement of high-temperature properties of sinter and coke
(5) Maintenance of a uniform descent of burden. The following measures would additionally be required for the future development of this technique:
(6) Examination of oxygen-atomizing method
(7) Measure for desulfurization.

The combination with the ultra-high pressure operation introduced at Nippon Steel’s Nagoya Works is considered an effective solution of these problems.

2. Injection of Reducing Gas

The quantity of injection of oil through the tuyere with the simultaneous use of oxygen enrichment is still limited by the restrictions described in the section of III. 1. The blast furnace tuyere is to furnish the hearth with an enough heat, to accelerate metallurgical reactions and to give the heat for melting of pig iron and slag. Thus, the restriction by the theoretical flame temperature originates from these purposes of the tuyere. In a blast furnace, the high temperature zone of above 1000°C requires an energy of about 300 000 kcal/tHM, even if the solution loss is not taken into account, and this corresponds to a coke rate of about 200 kg/tHM. If gas necessary for reduction
can be produced at a lower cost than that produced from coke, the injection of such lower-cost gas but with the restrictions by the flame temperature at tuyere would give a higher versatility.

To obtain the lowest fuel rate in a blast furnace, it is necessary to cause direct reduction to some extent in the lower part of the furnace and to use produced CO for the indirect reduction. The injection of reducing gas is however based on the idea to reduce ore indirectly as far as possible and save coke and heat energy required for the direct reduction. As already reported,26) this causes an increase in the total amount of reducing gas required per ton of pig iron, and this technology is not practically applicable unless the costs of injection and reducing gas is less than 4 yen per Nm³. This is however a method capable of injecting alternative fuel in a large quantity. In an experiment carried out in the experimental blast furnace of Nippon Kokan's Technical Research Center as shown in Fig. 7,15) this method with 220 kg/tHM of oil reduced the coke rate by about 210 kg/tHM and permits injection of a larger quantity.

The superiority still held by the blast furnace process in spite of the development of a number of direct reduction processes is attributable to its advantages over the conventional direct reduction processes in all the aspects including sticking of ores, ununiformity in product reducibility due to gas and burden distribution, withdrawal of products and production scale. Injection of reducing gas into blast furnace would make the full use of the maximum advantages of blast furnace and minimizes the consumption of strongly coking coal, and is thus the combination of the blast furnace and the direct reduction. Future progress of the FTG process of Nippon Steel14) and the technique developed at Nippon Kokan15) is expected.

V. Establishment of Injection Technique Suitable for Diversified Alternative Fuels

As shown above, difficulty in procuring coking coals, price increase of petroleum and shortage of low-sulfur oil in the future, and the necessity of preventing air and water pollution suggest the future necessity to inject crude oil, naphtha and other fuels which have never been employed in blast furnace. Table 3 roughly gives energies to be consumed in Japan in 1975.27)

In employing such a raw material in blast furnaces in the future, various problems will be encountered. When these problems will have successfully been solved, the fuel injection would be directed toward using crude oil or naphtha into blast furnace and simultaneously applying the oil injection and the desulfurization outside the furnace. However, it is an indispensable responsibility to exclude absolutely new pollution problems as a result. Against difficulties in the future, blast furnace metallurgists must solve such problems and establish technologies satisfying these diverse requirements in close cooperation with experts in the other fields.

VI. Conclusion

Due to the shortage of coking coals, it is sometimes discussed whether the age of direct reduction by the use of nuclear energy should be just ahead. The use of nuclear energy comprises however difficulties in necessary fuel sources and in its utilization. Therefore, the present author considers that a long time is needed for the application of atomic energy to iron making partly because of the too low productivity of the direct reduction process. A production process, well competing with the blast furnace which daily produces 10 000 t per production unit, will not be achieved so soon. Resources for petrochemical fuels, which are not of course infinite, seem to be capable of meeting the demand for another several tens of years, according to a report of the International Iron and Steel Institute. It would be our mission for us, blast furnace metallurgists, to make efforts so that the maximum blast furnace efficiency may be achieved through the careful use of these petrochemical fuels by the effective use of the other alternative fuels.

The fuel injection technologies for blast furnaces in Japan have thus overcome the difficulties in some extents and give successful results as shown above.

REFERENCES

5) BFI Committee: BFI Committee Report, (Oct. 1966), 91.

Table 3. Prospect of various fuels to be supplied in Japan in 1975

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Proportion in 10³ t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy oil</td>
<td>2.250 x 10³</td>
</tr>
<tr>
<td>Naphtha</td>
<td>0.470 x 10³</td>
</tr>
<tr>
<td>LPG</td>
<td>0.11 x 10³</td>
</tr>
<tr>
<td>LNG</td>
<td>0.005 x 10³ + α</td>
</tr>
</tbody>
</table>

Report