INVESTIGATION OF TECHNOLOGY TRENDS IN DECREASING BLAST FURNACE FUEL RATIO[1]

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Abstract

Blast furnace (BF) ironmaking is the most mature and efficient process at present. With the shortage of resource and industrial pollution increasing, how to furtherly decrease the fuel ratio becomes one of the important factors which restrict BF development. This paper analyzed the methods to decrease the fuel ratio from the viewpoint of increasing indirection reduction (IR) and decreasing heat consumption. Then, the methods to enlarge coke-saving potential by using metalized burden and high-reactivity coke were investigated. The results show that under the background of highly raw material quantity and operation level, comparing large BF with the small one, IR degree of large BF is relatively low, and the heat consumption (per ton of hot metal) is also different because of the difference in heat load and heat radiation. Increasing the coupling effect of reduction and gasification in thermal reserve zone, reduction efficiency increased in shaft, and the direction reduction degree in the lower part decreased, which shows the importance of rational allocation of direction reduction in BF. Using metalized burdens decreases the fuel consumption, as well as improves the permeability, while the problem of high melting temperature should be noted, to resolve which, metalized burdens should have high carbon content. Using high reactivity coke in BF could increase the reduction efficiency, as well as improve the permeability of cohesive dropping zone significantly.

Key words: Blast furnace; Fuel ratio; Metalized burden; High-reactivity coke.

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[1] *Technical contribution to the 6th International Congress on the Science and Technology of Ironmaking – ICSTI, 42nd International Meeting on Ironmaking and 13th International Symposium on Iron Ore, October 14th to 18th, 2012, Rio de Janeiro, RJ, Brazil.*

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1 INTRODUCTION

Blast furnace (BF) ironmaking process is the most mature and efficient process at present by the development of recent several-hundred years. However, it still faces some problems as followings for its further development in future. (i) The technologies such as beneficiated materials, oxygen-enriched blast, high temperature blast, pullverized coal injection, and low-Si operation etc. have been widely used in BF, which make the reduction efficiency and reduction agent rate improved than before, but it's very difficult to further improve its properties; (ii) with the worsen trend in the quality of iron ores and coal, the consumption of iron ores is increasing. Iron ores with high Al_2O_3 and high crystal water have to be used for ironmaking. At the same time, coal reserve is decreasing yearly, and the quality of the fuel used for BF is decreasing; (iii) coking coal reserve is also decreasing, which makes it difficult to ample supply for BF ironmaking all over the word; and (iv) problem of CO_2 emission of BF has been more critical. General technic used on BF is slightly helpful for CO_2 emission decreasing. Althouth pulverized coal injection could decrease the consumption of coke, it's not helpful for environmental load in BF ironmaking process system [1-4].

The core problems of the above is how to further improve the BF reduction efficiency and decrease the reduction agent rate under the condition of worsen raw materials of iron ores and fuel resources. Recently, many researches have done efforts on it. For example, the full oxygen BF ironmaking process is in research in some countries, which showed an increasing product efficiency. And in Japan, some researchers focused on charging ferrocoke in BF to increase the reduction efficiency[1,2,4,5]. All these methods obtained the improvement in BF ironmaking process. In this paper, the technology trends in further decreaing the fuel ratio will be disscussed from the view point of ironmaking theories.

2 ANALYSIS OF THE METHODS TO DECREASE THE FUEL RATIO BASED ON THE RELATIONSHIP BETWEEN DIRECT REDUCTION DEGREE AND CARBON CONSUMPTION

2.1 Relationship between Direct Reduction Degree and Carbon Consumption

Based on the iron ore direct reduction concept of M. A. Pavlov, Prof. A. H. Pamm et al. researched the relationship between direct reduction degree and carbon consumption by a diagram, which is shown in Figure 1.[6] In the figure, direct reduction degree is defined as followings.

$$r_d = \frac{Fe_d(FeO \rightarrow Fe)}{Fe_t} \qquad \text{Equation 1}$$

Where, $Fe_d(FeO \rightarrow Fe)$: the metal iron which was direct reduced by FeO for per ton of hot metal (HM); and Fe_t: the total reduced metal iron for per ton of HM.

As shown in the figure, line *a* shows the carbon consumption of carburization for per ton of HM. Line *b* shows the carbon consumption of direct reduction of FeO to Fe and carburization. The reaction is as Equation 2.

$$\mathrm{FeO + C = Fe + CO} \qquad \text{Equation 2}$$

Line *c* shows the carbon consumption of indirect reduction of FeO to Fe and the carburization. The reaction is as Equation 3.

$$FeO + CO = Fe + CO_2 \qquad \text{Equation 3}$$

Line *b* and Line *c* considers the carbon consumption of reducing agent and carburization for blast furnace. In this condition, the intersection point O' of line *b* and line *c* means the lowest carbon consumption without considering the heat consumption in blast furnace, and the corresponded direction reduction degree r_{d0} could be calculated. If only considering the heat consumption of the reduction, the relation between carbon consumption and direct reduction degree could be calculated by the heat balance of blast furnace, which was shown in line *d*. Therefore, considering the heat consumption, reducing agent and carburization, the relationship of the carbon consumption and direct reduction degree could be shown as the section of line AO and OB, and point O is the intersection of line *c* and *d*.

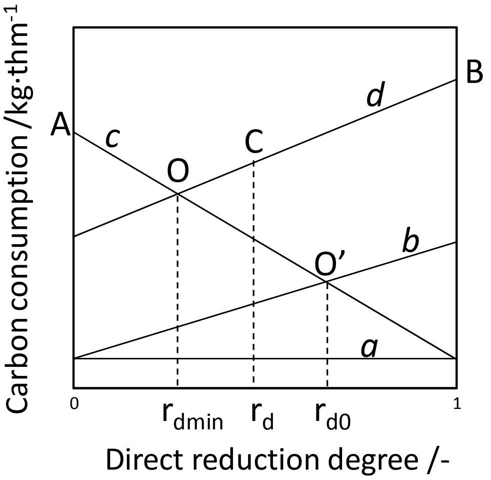

Figure 1. The relationship between carbon sumption and direct reduction degree.

As shown in Figure 1, the lowest carbon consumption could be obtained at point O, and the direct reduction under this condition is r_{dmin}, which is generally in the range of 0.2-0.3. In BF operation in China, the direct reduction is usually in the range of 0.4-0.5, higher than r_{dmin}. In order to further decrease the carbon consumption in a practical blast furnace, the solution could be analyzed by Figure 1. One method is to decrease the direct reduction degree to near r_{dmin}, which makes the point C close to point O, and the carbon consumption decreased. The other method is to decrease the carbon consumption of heat, which would shift down line *d*, and then the intersection point of O would also shift to right. In this condition, the r_{dmin} would be increased, the distance between O and C will be closed, and the carbon consumption would also be close to the lowest carbon consumption of O point.

Therefore, from Figure 1 it could be concluded that to further decrease the fuel consumption of a practical blast furnace, the direct reduction degree or the carbon consumption used for heat supply should be decreased.

2.2 Relationship between Direct Reduction Degree and Carbon Consumption of the Practical BF

To further analyze the relationship between direct reduction degree and carbon consumption, two different blast furnaces are studied. The volume of one BF is

4966 m^3 and another is 750 m³. By using the practical production data of two BFs, The relationship of the direct reduction degree and carbon consumption could be obtained, as shown in Figure 2 and Figure 3. Figure 2 presents the large BF of 4966 m^3 and Figure 3 presents the small BF of 750 m³. Because of the reduction of iron ore by H_2, the scale of the direct reduction degree (abscissa) is less than 1 in Figures 1 and 2. The data of Figures 2 and 3 in detail are summarized in Table 1. The practical direct reduction degree of the large BF is 0.408 while the r_{dmin} is 0.342. The practical direct reduction degree of the small BF is 0.439 and the r_{dmin} is 0.349. The results illustrates that the large BF operates better than the small BF with a lower direct reduction degree and lower carbon consumption. Even the volumes of BF are different, their carbon consumption of heat are close, which makes the lowest carbon consumption (ordinate of point O) has small difference.

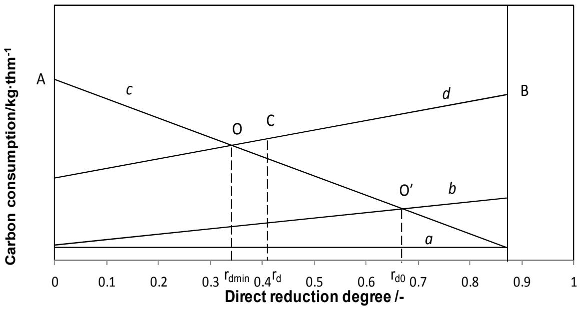

Figure 2. Relationship of direct reduction degree and carbon consumption of large BF.

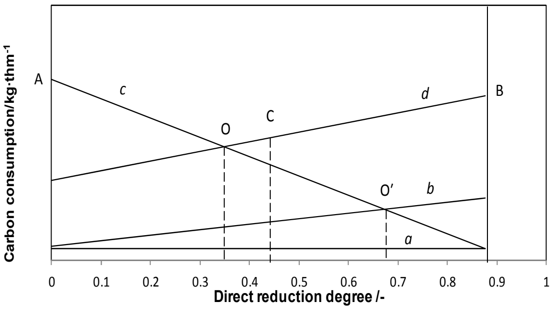

Figure 3. Relationship of direct reduction degree and carbon consumption of small BF.

Table 1. Direct reduction degree of two different BFs

	r_{dmin}	r_d	r_{d0}
Large BF	0.342	0.408	0.671
Small BF	0.349	0.439	0.676

To further analyze the two blast furnaces, the gas utilization efficiency and heat loss are studied. Figure 4 shows the gas utilization efficiency of two blast furnaces in one month. The average gas utilization efficiency in one month is 51.86% and 46.53% of large BF and small BF respectively. As shown in Figure 4, the gas utilization efficiency of large BF in a month is not only higher but also much steadier than that of small BF, which indicated that the gas flow distribution in the large BF is much better than that in the small BF.

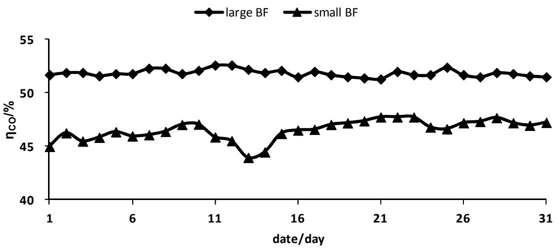

Figure 4. Gas utilization efficiency of large BF and small BF.

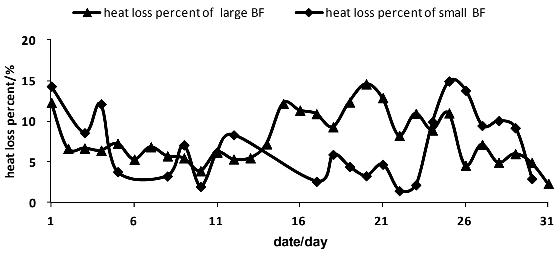

Figure 5. Heat loss percent of the large BF and small BF.

The percentage of heat loss is also shown in Figure 5. Rejecting several abnormal operation days, the heat loss percentage of large BF in one month is steadier than that of small BF and the average heat loss percent of large BF and small BF is 7.86%

and 6.47% respectively. The difference of them is mainly caused by the heat load and heat radiation. Compared with the samll BF, the large one has relatively low heat load and heat radiation for per ton of HM.

For the general situation, in practical production the methods such as using iron ores with good reduction ability, improving the gas flow distribution etc. should be applied to increase the indirect reduction. Moreover, the measures such as improving iron ore grade, no limestone charging, low top temperature, using reasonable cooling system, etc. should be applied to reduce the heat consumption. Nowadays, maximization of BF is the trend, which could greatly decreasing the carbon consumptiong compared with the small BF, but the conditions of iron ores, coal and coke must be considered.

3 ANALYSIS OF INCREASING THE COKE-SAVING POTENTIAL BASED ON RIST DIAGRAM

3.1 Rist Diagram

The Rist diagram is shown in Figure 6. The solid dark line (line AP) is the operation curve, and the dotted line (line A'P) is the ultimate operation curve which was limited by the chemical reaction equilibrium and thermal equilibrium. From Rist diagram, it could be analyzed that to further improve the efficiency of furnace inner reactions, it is necessary to shift the operation curve AE towards the W point, which would decrease the slope difference between the operation curve and the ultimate curve and increase the reaction efficiency of the shaft (which was defined as GZ/GW). However, as it is mentioned in the introduction part, under the present operation condition, it is difficult to further decrease the slope of AP if the slope of A'P is not changed. Therefore, in order to further increase the coke-saving potential, (1) to decrease the ordinate of W, which could be realized by using metalized burden; (2) to increase the abscissa of W, which means to lower the thermal reserve zone temperature and shift W point towards the high η_{CO} side (η_{CO}=$CO_2/(CO+CO_2)$), increase the reduction driving force, which is the difference between actual η_{CO} and the η_{CO} at the reduction equilibrium point, and thus accelerate the reduction of ore[7-11].

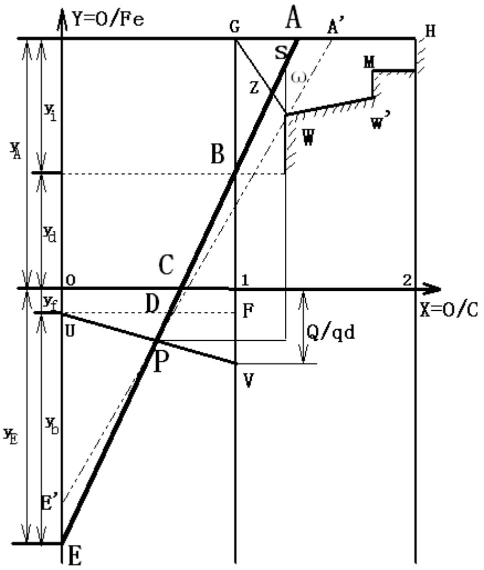

Figure 6. Rist diagram.

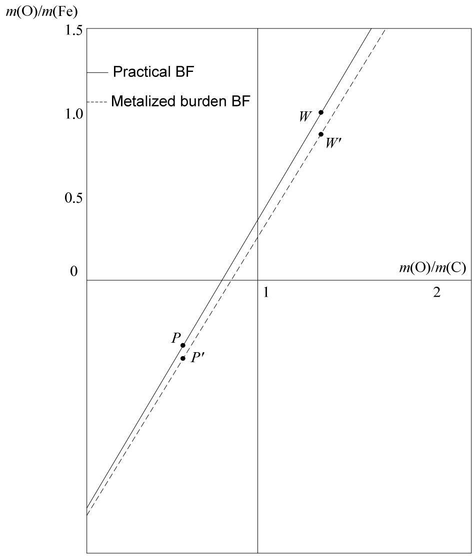

Figure 7. Rist diagram of using metalized burden.

3.2 Rist Diagram of Using Metalized Burden in BF

Using metalized burden in the BF would decrease the ordinate of W because FeO is partly replaced by Fe in the burden. As the FeO content decreases, the reduced iron in the BF also decreases. Thermal consumption varied with the reduced iron, which makes the thermal equilibrium point P change. Influence of metalized burden on BF Rist diagram is shown in Figure 7.
Moikin, Bokovikov, Babushkin[12] analysized the BF operation on metalized burden by methematical mo delling, and the results showed that coke consumption should fall by 4.0-5.4% and furnace productivity rise by 4.4-4.7% for each 10% of burden metallization. Chu et al.[13] and Pokhvisnev et al.[14] also studied the influnce of metalized burden on BF and got the conclusion that CO utilization of top gas is enhanced and the ratio of direct reduction is decreased by metalized burden charging.

3.3 Rist diagram of Using High Reactivity Coke in BF

Charging high reactivity coke in BF is another method to improve the coke-saving potential. The endothermic coke gasification reaction makes the heat conservation zone temperature decrease, and the CO equilibrium concentration decreases, and then makes the chemistry equilibrium point W shift to right. As the improvement of reduction efficiency, the heat consumption at high temperature zone decreases, which makes the thermal equilibrium point P shift. The Rist diagram of using high reactivity coke is shown in Figure 8, in which the new ultimate operation curve has a smaller gradient, which means the coke-saving potential is enlarged.

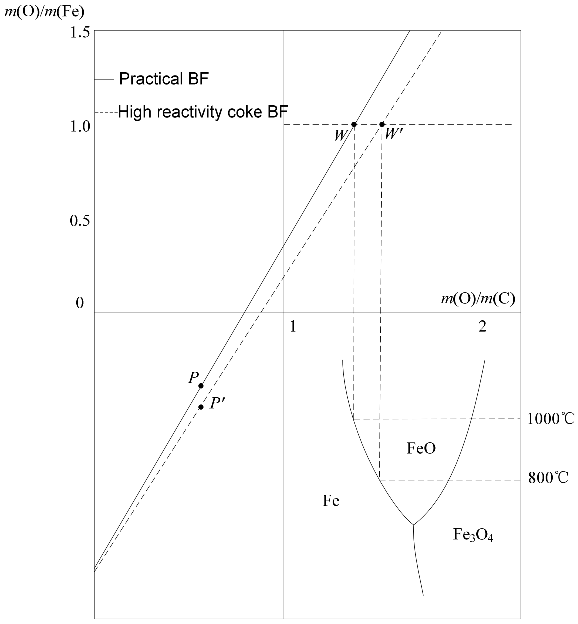

Figure 8. Rist diagram of using high reactivity coke.

The influence of coke reactivity on iron ore reduciton was experimentally analyzed and the results are shown in Figures 9-11. Two kinds of coke were selected: metallurgical coke with relatively low reactivity (CRI is 25%), and high reactivity coke (CRI is higher than 50%). Figure 9 and Figure 10 shows the CO and CO_2 concentration during the reduction experiment respectively. Comparing the CO and CO_2 concentration, the experiment using high reactivity has relatively high CO concentration and low CO_2 concentration which was caused by the improvement in coke gasification and iron ore reduction. Figure 11 shows the rion ore reduction degree after experiment, which proved that the high reactivity coke could improve the iron ore reduction in BF lump zone[15]. The high reactivity coke improved the direct reduction in BF lump zone, at the same time decreaed the direct reduction in the lower part. The partically movement of direct reduction from the lower part to the lump zone increased the indirect reduction degree in lump zone and indicated that it is importance to allocate the direction reduction rationally in BF.

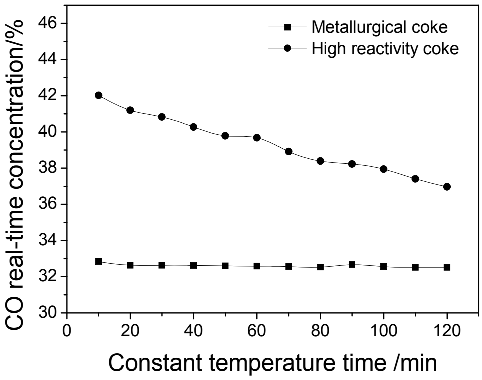

Figure 9. Effect of different reactivity coke on CO concentration in burden layer.

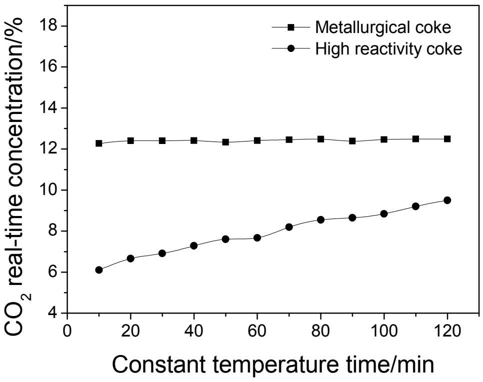

Figure 10. Effect of different reactivity coke on CO_2 concentration in material layer.

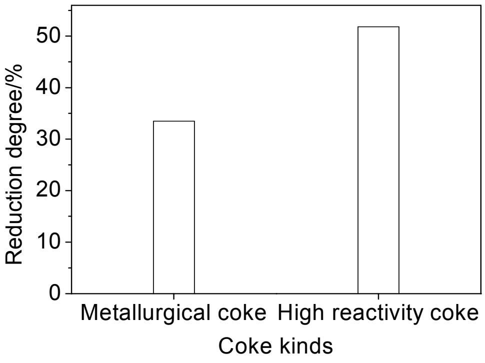

Figure 11. Effect of different reactivity coke on reduction degree of iron ore.

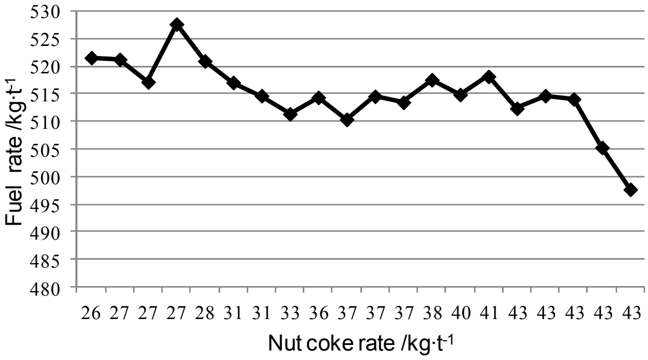

Figure 12. Relationship of the nut coke rate and fuel rate for the Stainless Steel Plant of Baosteel.

Figure 12 shows the practical BF fuel ratio of the Stainless Steel Plant of Baosteel (Shanghai, China) under the condition of using nut coke. Compared with the normal size coke, the nut coke has large specific surface area, so it has relatviely high reactivity. The Stainless Steel Plant of Baosteel had a series of test of nut coke in September of 2009, and the nut coke rate varies from 25 $kg{\cdot}t^{-1}$ to 40 $kg{\cdot}t^{-1}$. As shown in Figure 12, with the increasing of nut coke rate, the fuel has a decreasing trend and 1 kg nut coke saved 1.33 kg fuel in average. These practical data also proved that the fuel rate of BF could be decreased by using high reactivity coke.

4 INFLUENCE OF METALIZED BURDEN AND HIGHLY REACTIVE COKE ON IRON ORE SOFTENING DROPPING PROPERTIES

The softening dropping properties of iron ores in BF affect the cohesive zone properties, such as the position and the thickness of the cohesive zone, the permeability of the cohesive zone and the pressure drop of the gas flow through the cohesive zone. Therefore, in this part the iron ore softening dropping properties in the conditions of using metalized burden and highly reactive coke are analyzed.

4.1 Influence of Metalized Burden on Iron Ore Softening Dropping Properties

During the reduction of iron ore, the generated FeO affects the softening properties; the carburization affects the dropping properties; the molten slag affects the pressure drop of the gas flow through the cohesive zone.

Table 2 shows the softening dropping properties of the different metalized burden. In the table, metallization rate and FeO content of the different burden is also given. Ts in the table is softening temperature, and Td is dropping temperature. They are evaluated by the molten drop test. During the molten drop test, the temperature that the height of the burden bed decreasing 10% is evaluated as Ts, and the temperature that the first metal iron dropped is evaluated as the Td. The highest pressure drop during the test is evaluated as $\triangle P_{max}$, and average pressure drop during the molten drop is calculated as $\triangle P_{av}$.

Table 2. Characteristics of different burden

Burden	Metallization rate /%	FeO/mass%	C/mass%	Ts/□	Td/□	$\triangle P_{max}$/Pa	$\triangle P_{av}$/Pa
A	0	5.55	3.16	1,200	1,425	3,270	1,342
B	45	51.21	2.95	1,045	1,487	1,400	393
C	78	24.82	3.93	1,146	1,375	660	148

The reduction process of burden A is $Fe_2O_3 \rightarrow Fe_3O_4 \rightarrow FeO \rightarrow Fe$, and that of burden B and C is $FeO \rightarrow Fe$. Therefore, the metalized burden of B and C have more content of FeO at the beginning of the test, which decreased the softening temperature compared with burden A. As for the burden B and C, although the FeO content of B is higher, it would be decreased by reduction to Fe, therefore, the Ts of burden B is lower than that of C.

Figure 13 shows relation between Fe content and C content in Fe-C phase diagram. The dropping temperature of metalized burden decreases with increase of C content in Fe-C phase. As shown in Table 1, the dropping temperature of burden B is the highest, and that of burden C is the lowest. The main reason of it is that the higher carbon content in the molten iron of burden C decreased the dropping temperature.

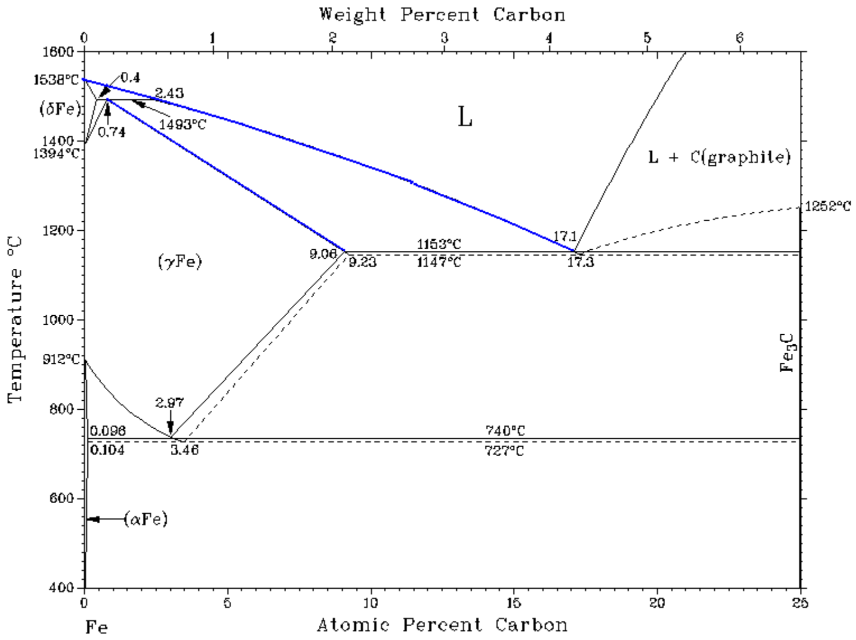

Figure 13. Fe-C phase diagram.

As shown in Table 2, the pressure drop of these burdens is also different. The difference of it is mainly due to slag properties. The burden with high metallization rate, the maxium pressure drop and the average pressure drop is relatively low, which indicated that using metalized burden could improve the pemeability of the burden bed.

From these experimental data, it could be concluded that metalized burden in BF could decrease the pressure drop of the gas flow through the cohesive zone, which would improve the pemeability of the burden bed. However, if the metalized burden such as scrap, direct reduction iron made by Midrex process, which has relatively low carbon content, the dropping temperature would be increased because the metalized burden is more difficult to carborization comparied with the iron ores without prereduction. Therefore, in order to further improve the softenning dropping properties of the burden, the metalized burden with high carbon conten should be selected, such as the carbon-bearing pellet and the direct reduction iron made by totary hearth furnace.

4.2 Influence of High Reactivity Coke on Iron Ore Softening Dropping Properties

As it has been analyzed formerly, high reactivity coke used in BF could improve the iron ore reduction because of the coupling effect of iron ore reduction and coke gasification. The improved reduction reaction of iron ore would make the FeO reduced earlier compared with that using the relatively low reactivity coke. Therefore, the softening beginning temperature in this condition would be decreased, and the temperature range of the softening would be enlarged. As for the dropping temperature, in the earlier period of softening, the pressure drop would be slightly increased because of the FeO production; in the middle and late period of the softening, the pressure drop would be greatly decreased.

Table 3 Effect of coke reactivity on softening dropping properties of metalized burden

Samples	Ts/□	Ts-m/□	Td/□	△Pmax/Pa	△Pav/Pa
Coke A	1,200	90	1,413	3,200	1,569
Coke B	1,160	160	1,380	1,860	1,282

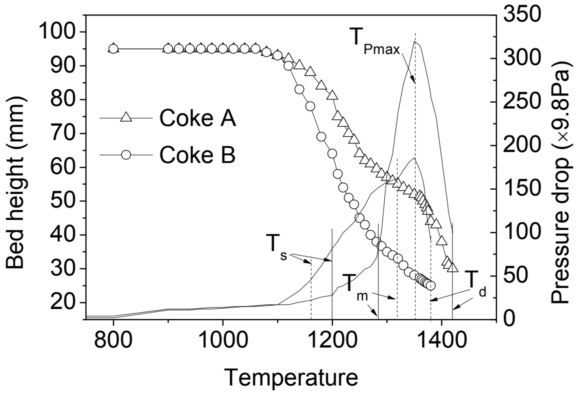

Figure 14. Effect of coke reactivity on softtening dropping properties.

Table 3 shows the effect of coke reactivity on softening dropping properties of metalized burden. In the table, coke A is the metallurgical coke which was from Baosteel (Shanghai, China), coke B is the high reactivity coke. The burden height and the pressure drop during the test are shown in Figure 14. In Table 3, Ts-m is the temperature range of softening and melting.

As shown in Table 3, comparing with the coke A, using high reactivity coke B could decrease the softening temperature and dropping temperature of the burden, and shorten softening-melting temperature range. As shown in Figure 14, the pressure drop during the experiment of the two kinds of coke is also different. Although using high reactivity coke could increase the pressure firstly, the maximum pressure drop is greatly decreased comparing with that using coke A. Therefore, the average pressure drop and the permeability of the burden bed could be improved by using high reactivity coke.

5 CONCLUSIONS

This paper investigated the technology trends in decreasing BF fuel ratio. The methods of further decreasing the fuel ratio was analyzed by using the relationship between carbon consumption and direct reduction degree, and then the Rist diagram is used to analyze the methods to increase the coke-saving potential. After that, the some methods were proposed for furthering decreasing the fuel ratio of BF ironmaking. The results show that:

- Under the background of highly raw material quantity (sinter and pellet) and operation level, comparing large BF with the small one, indirect reduction degree of large BF is relatively low, and the heat consumption is also different because of the difference in heat load and heat radiation.
- Increasing the coupling effect of iron ore reduction and coke gasification in thermal reserve zone, reduction efficiency increased in shaft, and the direction reduction degree in the lower part decreased, which shows the importance of rational allocation of direction reduction in BF.
- Using metalized burden could not only decrease the fuel consumption, but also improves the permeability of cohesive zone in BF, while the problem of

high melting temperature should be noted, to resolve which, metalized burdens should have high carbon content.

- Using high reactivity coke in BF could increase the reduction efficiency, as well as improve the permeability of cohesive dropping zone significantly.

Acknowledgement

The financial support of the National Natural Science Foundation of China (50974143) and Fundamental Research Funds for the Central Universities (FRF-TP-12-021A) is gratefully acknowledged.

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