Suitable Combustion Rate of Coal in Blast Furnace [1]

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ABSTRACT

One of the actions of coke in blast furnace is to offer a reaction space and gas passage. The damage of coke is an important problem for blast furnaces with large coal rate. This worsens the effect of coke as framework of the burden. The decreasing of coke proportion in burden is the main reason for that. Combustion rate of injected coal is an important parameter. To rising it is an important target all along. However, it should be more discussed under large coal rate. The non-combusted carbon in coal char has an important action to protect the coke. This effect and the suitable combustion rate of coal will be mainly discussed in this paper.

KEY WORDS coal injection, char, blast furnace.

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Coal injection is the most important technical development of blast furnace production in recent years. A coal rate over 200 $kg.t^{-1}$ is already familiar for advanced blast furnaces. However, larger coal rate is still an important target for ironmaking. The methods for increasing coal rate are most in allusion to keep the combustion temperature and conditions for gas flow. Because the coal char can worsen the condition for gas flow, to increase the combustion rate of coal is an important target for research and production.

Beside the action mentioned above, coal char has also a positive function to protect coke against the gasification reaction with CO_2 and H_2O. A research work was done to estimate this function and to discuss about the suitable combustion rate under large coal rate.

1 Combustion rate of carbon in coal

Under temperature in front of tuyeres of blast furnace, the gasifiable substances other than fixed carbon in coal will be all gasified. Therefore, the significative parameter about coal combustion is the combustion rate of carbon of injected coal. The combustion rate of carbon r_C is defined as the proportion of gasified carbon to total carbon in combustion zone of blast furnace.

According to the results of two industrial experiments about coal injection in Shoudu Steel and Anshan Steel in China, the carbon quantity of coal in top dust was between 0.5 and 0.8% of the injected quantity[1]. The average value of the proportion of waste carbon to total carbon r_W was about 0.6%. That is to say, about 99.4% of carbon in injected coal is gasified or used in the blast furnace.

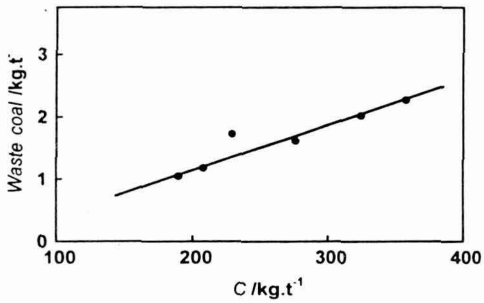

Figure 1 Waste carbon in relationship to coal rate according to Shoudu Steel

Figure 1 shows the test results of Shoudu Steel about the relationship between the waste coal found in top dust and the coke rate C[1].

2 Behavior of carbon in injected coal

Carbon in injected coal can be consumed in following ways:

1. Combusted in front of tuyeres.
2. Used for carburization of pig iron.
3. Used for direct reduction or gasification reaction.
4. Carried by gas out of the furnace.

5. Carried by hot metal or slag out of the furnace.

For a blast furnace in normal state, the last way can be ignored. As mentioned above, the waste carbon in top gas is about 0.6%. The rest 99.4% is consumed in the first 3 ways. The consumption of carbon in the first 3 ways is only to instead of coke and its distribution has no direct influence on the energy consumption or general heat balance. Therefore, the important thing is the indirect influence of it on the operating state of the furnace.

Shoudu Steel has anatomized a small blast furnace in 1981 to find out the distribution of non-combusted coal in blast furnace[2]. Coal char has been found in all parts of the furnace but the most accumulation was under the raceway in front of the tuyeres. A research using a cool model[1] supported this results. According to this simulating research, the most accumulation was also under the raceway in front of the tuyeres and the second most part was between the cohesive zone and the plane of the tuyeres. In stabilization, the accumulated coal char under the raceway is under a dynamic equilibrium. New coal char goes into it and old coal char is carried by gas out of it.

According to the state of a blast furnace, the condition for reactions with coal char in the molten bath like carburization and reduction is not so good. The most coal char is likely to be carried by the gas and used for the reactions in the part of the furnace in front of or above the tuyeres. For a blast furnace with large coal rate, this is just the key zone, in which the coke is badly damaged.

According to the experience of Anshan Steel, the coke size in front of the tuyeres with a coal rate over 200 kg.t^{-1} will be much smaller than that in normal state. Therefore, the reactions with coal char can protect the coke.

3 Gasification of carbon

The difference of reactive abilities of gasification reaction between coal char and coke is very important for above mentioned protection behavior of coal char. A series of gasification tests was carried out to get the kinetic parameters of different coal chars and cokes. Figure 2 shows the equipment for the tests. The velocity constant of gasification reaction was calculated using following formula:

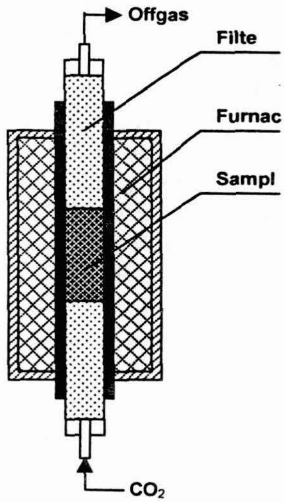

Figure 2 Equipment for gasification test

$$\ln\frac{(1-F)^2}{F} = \ln\frac{(1-F_0)^2}{F_0} + kC_0 t$$

In this formula, F is the transform rate of CO_2 in offgas, t is time, F_0 is the transform rate of CO_2 in offgas when t=0, C_0 is the density of CO_2 and k is the target parameter. This is a statistical formula of the data from the test. Please see reference 3 for the principle[3].

Table I Kinetic parameters of carbon gasification reaction

Name	Kind	A /m^3.kmol^{-1}.s^{-1}	E / J.mol^{-1}
Holinhe coal	Lignet	2.08×10^{12}	316 855
Datong coal	Bituminous	3.61×10^{10}	329 517
Shenfu coal	Bituminous	7.44×10^{10}	328 869
Shenmu coal	Bituminous	1.28×10^{10}	291 928
Yima coal	Bituminous	1.27×10^{10}	292 787
Yangquan coal	Anthracite	9.80×10^{9}	348 307
Anshan Steel	Coke	1.77×10^{10}	467 741

Table 1 shows the kinetic parameters of gasification reaction with CO_2 of different materials. The gas flow velocity was 0.37 m.s^{-1} and the sample size was 6 to 10 mush. Test temperature was from 1000 °C to 1400 °C. Increase of gas flow velocity and decrease of sample size cannot change the results of the test. Because the gas flow velocity was lower and sample size was higher than that in a blast furnace, the results may be used for blast furnace.

Figure 3 gives a compare of the velocity constants in relationship to the temperature.

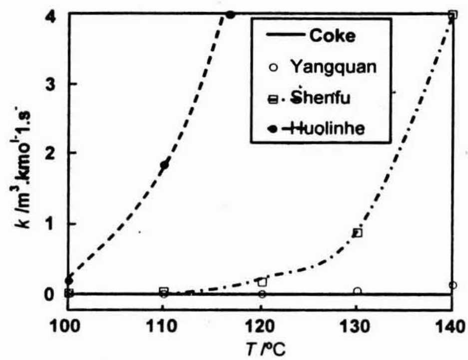

Figure 3 Reduction velocity

The reaction velocity of anthracite (Yangquan) is nearly the same as coke. Therefore, the protection effect of Yangquang coal is the worst of above coals. The most anthracites are like Yangquan coal. Anthracite has an important strong point. Its content of fixed carbon is very high. It is specially suitable for blast furnaces with low blast temperature. That is perhaps one of the important reasons against the increasing of coal rate for such blast furnaces.

Lignet coal (Huolinhe) has the highst reaction velocity but its composition is not suitable for injection. Huolinhe coal has a volatile content about 43% and a water content of hydration about 15%. For injection in great mass, a serious falling of combustion temperature may be caused by the high volatile, especially by the water of hydration. Therefore, lignet is also not a suitable kind of coals for injection.

Bituminous coals like Shenfu have mezzo volatile and fixed carbon contents. There is no problem against the increasing of coal rate, especially for the blast furnaces with enough blast temperature. It can be seen in figure 3 that the reaction velocity of bituminous is much higher than that of coke. Therefore, bituminus coals must have a effective protection behavior upon the coke. Baoshan Steel and Anshan Steel in China have increased their coal rate with big ranges after they have changed their injection coals from anthracite to bituminous coal. The protection effect should be an important reason for that.

Beside that, the coke size in a blast furnace is much larger than that in the test and the resistance of inside diffusion must decrease the velocity of gasification reaction. Therefore, The difference of reaction velocity between coal char and coke in blast furnaces will be more than that in the test.

4 Validate experiment

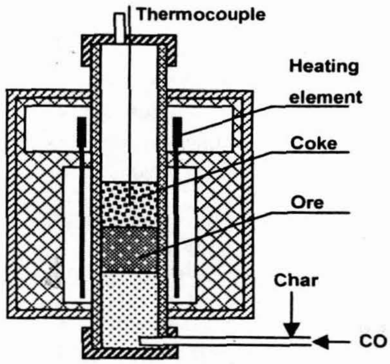

Figure 4 Equipment for validate experiment

To confirm the protection effect of coal char, a validate experiment was carried out using an equipment shown in figure 4.

The samples were 3 kg of iron ore and 0.6 kg of coke. They were preheated to 900 °C in protection atmosphere. Afterward, the temperature was continuously raised to 1200 °C in 4 hours and a gas mixture of CO (35 %) with N_2 was used to reduce the iron ore. Some coal char with a size under 60 mushes was equably injected together with the reduction gas through the samples. At the end of an experiment, the samples were cooled in protection atmosphere. The coke sample was quantified and analyzed to get the loss rate of carbon (L_C) during the experiment. Table 2 gives the main results.

Table II Main results of validate experiments

№	Coal char	Mass of coal char /kg	L_C /%
1		0	45.6
2	Shenfu	0.2	34.8
3	Shenfu	0.3	28.4
4	Shenfu	0.4	26.3
5	Shenfu	0.5	25.8
6	Shenfu	0.6	23.9
7	Huolinhe	0.4	18.8
8	Yangquan	0.4	31.6

Three trends can be seen through the results:

1. Coal char has strong protection effect on coke.

2. The reaction ability of coal char has strong influence on the protection effect. With the same quantity, coal char with

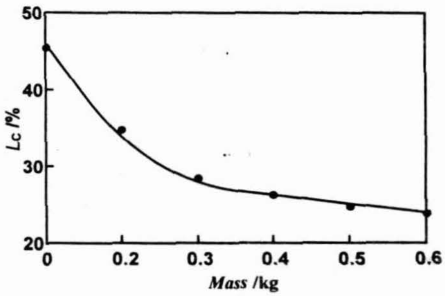

Figure 5 Influence of Shenfu coal char on carbon loss rate of coke

higher reaction ability has stronger protection effect.

3. Mass of coal char has also strong influence on the protection effect. Figure 5 shows the relationship between carbon loss rate of coke and the char mass of Shenfu coal.

5 Discussion

Carbon loss rate of coke is one of the most important parameters for coal injection. Coke strength falls with the rising of carbon loss rate. Figure 6 gives an overview of the relationship between coke strength S_C and carbon loss rate[4]. With large coal rate, the coke burthen is much heavier. Under this condition, the falling of coke strength must leads to a decrease of coke size in the blast furnace and that causes a worse condition for gas passing. Coke size or strength is especially important before the coke arrives the raceway.

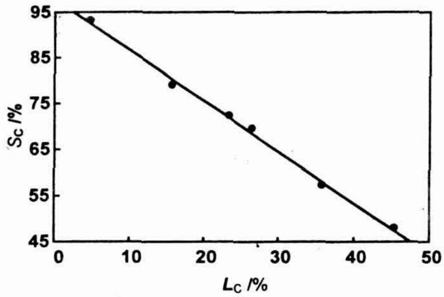

Figure 6 Coke strength in relationship with carbon loss

Above the tuyere level, carbon is used mainly for direct reduction and carburization. Carbon quantity for carburization is about 40 kg and for direct reduction is about 90 kg (r_d=0.45) for 1 ton pig iron. Suppose 50% of the carburization is carried out above the tuyere level, the whole carbon consume is about 110 kg.

According to the result of Baoshan Steel, 1 ton injected coal powder can approximately replace 0.85 ton coke. Suppose all carbon in coal is combusted in front of the tuyeres, the relationship between the loss rate of carbon above tuyere level and coal rate can be shown in figure 7. The carbon loss rate rises from about 25 % to about 50 % while the coal rate rises from 0 to 300 kg.t^{-1}. According to figure 6, the coke strength will decrease about 35 %. To decrease the carbon loss rate and keep the strength of is just the duty for coal char.

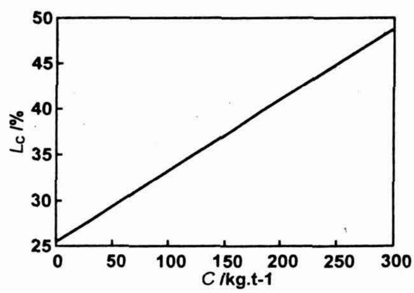

Figure 7 Relationship between loss rate of carbon and coal rate (r_C=1)

For a fine operated blast furnace, the CO utilization ratio is over 50%. However, this ratio in a large part of the furnace above the tuyeres is only under 10%. That is mainly decided by the thermodynamic rule. The temperature in this part is about or over 1000

°C. At such temperature, the utilization ratio of CO cannot be high. The most of this zone is under the cohesive zone.

The temperature in the most part of lumpish zone is at a low level. The high temperature region from 1000 °C to the start of the cohesive zone (about 1200 °C) is only a small part of it.The velocity constant of carbon gasification here is also low for coal char. In addition, there is not so much coal char accumulation. Most of the coal char passes fast with the gas through this region. Therefore, the consumption of coal char cannot be so much in the lumpish zone. The incoming quantity of coal char is unlikely much more than the outgoing quantity (about 0.6 %).

The cohesive zone is also a small region. The reaction condition for reduction is not so good here. The gas from lower part is high reductive and passes most through the coke window. Therefore, the consumption of coal char in this region can also be overlooked.

In the region between the cohesive zone and the tuyeres, the conditions for carbon gasification both of thermodynamics and kinetics are very good. Further more, the coal char in the gas is also most accumulated here by the filtration effect of the molten material and cohesive zone. At the temperature in this region, the velocity constant of gasification reaction for Shenfu coal is about 50 000 times higher than that for coke. Therefore, the most carbon in coal char can be gasified in this region, if it is not overmuch. During the experiments in Shoudu Steel and Anshan Steel, the coal rate has been severally increased to over 369 kg and 250 kg. The waste carbon was still less than 1 %. This fact suggested that the ability of blast furnace to accept and deal with non-combusted coal char is very strong. It is only important that the reactivity of coal must be high enough. There were experiences from blast furnaces, which use anthracite coal, that a lot of coal char goes out of the furnace with the gas, slag and iron, when too much coal was injected.

The carbon quantity of injected coal, which is used instead of coke above the tuyere level, is named as effective carbon and marked as C_e. According to above discussion, it can be calculated as fllows:

$$C_e = CC_t(1 - r_C - r_W)$$

Where, C_t is the carbon content of coal. It can be seen that the effective carbon is mainly decided by coal rate and combustion rate. Using the conditions of Baoshan Steel, the relationship between carbon loss rate and coal rate under different combustion rate was calculated as shown in table 3. The condition for table 3 is as follows:

Coke rate: 466 kg.t^{-1}, when C=0;

Fixed carbon content of coke: 85%.

Carbon content of coal: 72%.

Replace ratio: 0.85 (1 kg coal to 0.85 kg coke).

Table III Carbon loss rate of coke in relationship with coal rate and combustion rate /%

C / r_C	0	50	100	150	200	250	300	350	400
0.2	27.78	22.62	16.31	8.42	<0	<0	<0	<0	<0
0.3	27.78	23.62	18.53	12.17	3.99	<0	<0	<0	<0
0.4	27.78	24.62	20.75	15.92	9.71	1.43	<0	<0	<0
0.5	27.78	25.62	22.97	19.67	15.42	9.80	1.84	<0	<0
0.6	27.78	26.62	25.20	23.42	21.14	18.18	13.91	7.49	<0
0.7	27.78	27.62	27.42	27.17	26.85	26.55	25.98	25.11	23.67
0.8	27.78	28.62	29.64	30.92	32.57	34.92	41.90	42.74	50.06

In table III, there are some values below zero. That is to say, the coal rate is too high or the combustion rate is too low. In this case, the coal char is overmuch and unable to be fully used in the furnace. There are two ways for the unwanted part. The better one is as waste to be carried out of the furnace. The other one is to accumulate in the furnace and that will damage the normal operation. Under this condition, the fuel consumption is over the normal level or the heat is in short supply. To decrease the coal rate is a simple way to solve this problem. The other way is to increase the combustion rate. To select other coal with higher reactivity is a sane method to do that. According to refference 5, the combustion rate is about 0.48[5]. Under this condition, the limit of coal rate is about 300 $kg.t^{-1}$.

There is another rule for the relationship between L_C and C. The carbon loss rate of coke falls with the rising of coke rate under lower combustion rate and rises under higher combustion rate. Under present condition, L_C is a constant with a combustion rate about 0.72.

If the real combustion rate in blast furnace is about 0.5, the coke strength should be raised under larger coal rate according to table 3. On the other hand, the experience shows a fact that the coke size was decreased in front of the tuyeres under larger coal rate. There are two reasons to explain it. One of them is that the influence of coke strength cannot counteract the influence of the increase of coke burthen. The other is that the actual combustion rate is much more that 0.5. The best way to find the real reason is an industrial experiment for confirming the coal rate, under which, the overmuch coal char begins to appear. Using that coal rate, the real combustion rate can be calculated.

If the first one is the real reason, to use a lower coal rate and to keep a lower L_C is the only way to get better operating and technical parameters.

If the second one is the real reason, to decrease the combustion rate for higher coke strength is a sane method to solve the problem. Size of coal for injection is a good parameter to controll the combustion rate. Using larger coal size can decrease the production cost at the same time. In this way, a standard is needed to find the suitable combustion rate. Carbon loss rate of coke and coke burthen are two direct parameters for this. As mentioned above, the first one cannot be the standard and the second one is an incontrollable parameter under a certain coke rate. We use carbon burthen of coke at the tuyere level as the standard and mark it as B_C. That is a medial parameter between carbon loss rate and coke burthen. It is defined as the reciprocal of the carbon quantity in coke at the tuyere level:

$$B_C = \frac{1}{KC_f + C_e - C_C}$$

Where, K is coke rate in kg.t^{-1}, C_f is fixed carbon content of coke and C_C is carbon consumption above the tuyere level in kg.t^{-1} (about 110 kg). Table 4 gives the relationship between B_C, C and r_C under the same condition as Table 3.

Table IV Carbon burthen in relationship with coal rate and combustion rate /t.kg^{-1}

r_C \ C	0	50	100	150	200	250	300	350	400
0.2	0.00350	0.00359	0.00369	0.00379	0.00390	0.00403	0.00416	0.00429	0.00443
0.3	0.00350	0.00364	0.00379	0.00395	0.00413	0.00435	0.00457	0.00481	0.00508
0.4	0.00350	0.00368	0.00389	0.00413	0.00439	0.00472	0.00507	0.00547	0.00595
0.5	0.00350	0.00373	0.00401	0.00432	0.00469	0.00516	0.00569	0.00635	0.00718
0.6	0.00350	0.00378	0.00413	0.00453	0.00503	0.00568	0.00649	0.00756	0.00905
0.7	0.00350	0.00384	0.00425	0.00477	0.00542	0.00633	0.00755	0.00934	0.01224
0.8	0.00350	0.00389	0.00439	0.00503	0.00588	0.00715	0.00902	0.01221	0.01891

The industrial experiment shows that a coal rate of 200 kg.t^{-1} is acceptable. Suppose the combustion rate is about 0.5, the carbon burthen is about 0.0047. We use temporarily this value as the standard of B_C. A diagram can be made using this standard and above discussion as shown in figure 8.

There are three kurves in figure 8. Curve 1 is drawn according to B_C=0.0047. Curve 2 is drawn according to L_C=0. Curve 3 is a vertical line through the intersection of curve 1 and curve 2. The diagram is devided by the three curves in 4 parts.

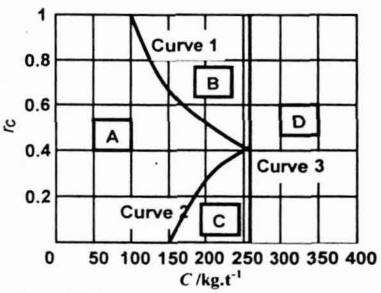

Figure 8 Diagram to confirm combustion rare

Part A is the suitable area for coal injection. In this area, the quantity of coal char is enough to save the coke and can also be fully used. This area is straiter at righter side. That is to say, the range of suitable combustion rate is smaller with highercoal rate. If the coal rate is too high, There is no suitable combustion rate to be selected.

In part B, the carbon burthen is too heavy. There is an economical method to solve this problem, namely using larger coal size to decrease the combustion rate.

Overmuch coal char appears in part C. In this area, higher combustion rate is needed. Using coal with higher reactivity is the most effective method to increase the combustion rate.

There is no suitable combustion rate for part D. In the upper area of this part, the carbon burthen is too heavy. In the lower area, the coal char is too much. In the middle area, the carbon burthen is too heavy and the coal char is too much. But then, curve 3 can be moved rightwards, for example through improvement of coke.

6 Conclusion

1. Coal char has strong effect to protect coke in blast furnace.
2. High reactivity is very important for injection coal.
3. Blast furnaces with large coal rate need enough but not overmuch coal char to protect the coke.
4. Low combustion rate of coal make overmuch coal char.
5. High combustion rate of coal damages the coke.
6. Suitable combustion rate of coal can be found in the diagram shown in figure

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