Investigation on Behavior of Unburnt Pulverized Coal in Blast Furnace

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In order to clarify the combustion reaction when PC (Pulverized Coal) is blown into the tuyeres of a blast furnace and the effects of resultant unburnt PC on reactions, in the furnace, some fundamental experiments were carried out. The main results obtained are as follows:

- (1) Most of PC blown through the tuyeres rapidly burns in the raceway.
- (2) Unburnt PC tends to adhere to the softened and fused ore bed.
- (3) Unburnt PC adhering to the ore bed is consumed by the direct reduction of FeO and improves the softening and melting-down properties of ores effectively.

In this way, PC entering inside the blast furnace without burning was found to be consumed effectively.

KEY WORDS: ironmaking; blast furnace process; pulverized coal injection; coke; unburnt pulverized coal; gasification.

1. Introduction

Pulverized coal (hereinafter referred to as PC) has been used more widely to have a stable operation of blast furnaces and to decrease the coke consumption.^{1,2)} Recent blast furnace operation has a problem on how to burn PC completely but this seems to have restriction on equipment and blowing conditions.

On the other hand, it has been empirically known that the injection of PC not only replaces coke partly with coal but also stabilizes the furnace performance. PC injection into the furnace has been recognized to have a greater effect than blast humidity but the reason has not been clear yet.

Unburnt PC was observed inside an operating blast furnace³⁾ and it was reported⁴⁾ that most of unburnt PC was preferentially gasified by CO₂ gas and thereby gave little effects on the pressure drop in the furnace. However, the behavior of unburnt PC in the blast furnace, namely the effects on gas flow and on various reactions in the furnace are not known. If unburnt PC generating in the furnace could be effectively consumed, a fairly large amount of PC injection into the furnace, use of various kinds of coal and mitigation of combustion and equipment conditions could be expected.

This paper describes the behavior of PC in the blast furnace through the investigation of the effects of unburnt PC injection into packed beds on the change in its residual amount and on the high-temperature properties of sinter.

2. Experimental Apparatus and Experimental Procedure

2.1. Combustion of Pulverized Coal

A single coal particle (weighed 3 to 7 mg and not a single particle in a strict sense) was burnt by spon-

taneous ignition, and its combustion was observed.

Fig. 1 shows the schematic experimental apparatus. The combustion air was made to flow at a given rate (20 NL/min) through the packed bed of small alumina balls and was heated up to a given temperature (800–1 200°C). A certain amount of PC was fixed to the end of the thermocouple and was put into a given position of the combustion chamber to burn. Temperature changes and combustion time were measured by the thermocouple. Further, the changes in the flames were detected through the condenser lens, amplified and connected to the electromagnetic oscillograph to measure ignition delay and combustion time. Australian coal crushed under 200 mesh having the properties given in Table 1 was used as a test PC.

2.2. Behavior of Sinter in High Temperature Gases with Unburnt Pulverized Coal

Fig. 2 shows the schematic experimental apparatus.

Fig. 1. Experimental apparatus for combustion of pulverized coal.

Table 1. Properties of pulverized coal.

FC (%)	VM (%)	Ash (%)	Density (g/cm ³)	Ultimate analysis (%)		
				C	H	N
58.8	38.3	9.1	0.86	83.5	4.5	2.1

Fig. 2. Experimental apparatus.

Sinter or coke was packed in the reaction tube. The particle size of samples was restricted to 20 ± 1 mm because of the tube diameter (70 mm). The bed was set to be 100 mm in height. Commercial sinter, the characteristics of which are shown in Table 2, was used as a sample. PC was prepared from the coal whose properties are shown in Table 1 and heated at 1500°C for 8 h to devolatilize. Table 2 shows the properties of the resultant PC. A given amount of the PC was fed by the screw feeder, transferred by N_2 and blown into the furnace with the reducing gas.

The experiments were carried out changing the temperature, the gas composition and the load.⁵⁾ The pressure drop in the sample layer and its shrinkage were measured and the waste gas was analysed. Most of the unburnt PC blown into the furnace remained in the sample layer, whereas the rest was discharged out of the system by the gas and was collected by two cyclones alternately at a given interval. The weight of materials captured in the sample layer was measured after the experiment.

Sintered ores, began to fuse over 1000°C , and this makes it difficult to measure the powder amount in the packed bed. In this case, the amount was calculated from the powder balance, because it was confirmed that the amount of the powder remaining in the sample in the low-temperature region was equal to the difference between the supply and the recovery.

3. Experimental Results and Discussion

3.1. Unburnt Pulverized Coal Caused by Imperfect Combustion

Fig. 3 shows the typical temperature changes and the results of measurement by the electromagnetic oscillograph. Pulverized coal at the point (a) in the furnace was heated and ignited at the point (b). The amount of volatile components and flame brightness decrease during the gaseous combustion and it finishes

Table 2. Properties of samples.

	Chemical compositions (%)						RI (%)	RDI (-3 mm%)
	T.Fe	FeO	CaO	SiO ₂	Al ₂ O ₃	MgO		
Sinter	55.6	5.89	9.70	5.81	2.11	1.45	64.1	36.1
FC (%)	Ash compositions (%)							
	T.Fe	CaO	SiO ₂	Al ₂ O ₃	MgO	Alkalis		
UPC*	92.3	0.2	1.1	2.8	3.0	0.1	0.02	

* Unburnt Pulver Coal

Fig. 3. Burning history of pulverized coal.

at the point (c). Subsequently, a part of residual carbon particles ignites and initiates solid combustion, reaching the maximum temperature at the point (e). Solid combustion finishes at the point (f), leaving ashes.

Fig. 3 shows that the ignition delay, the gaseous combustion time and the solid combustion time are about 500, 200 and 900 ms, respectively, and that the solid combustion time is about 4 to 5 times as long as that of gaseous combustion. Application of the square law⁶⁾ to the combustion temperature and the particle size enables to calculate the gaseous combustion and the solid combustion time in this experimental condition as follows:

$$D_0^2 = k_g t_g \quad (1)$$

$$D_0^2 = k_s t_s \quad (2)$$

$$D_0 = 2 \left(\frac{3}{4\pi\rho} M \right)^{1/3} \quad (3)$$

$$k_g = 0.0536 \text{ (cm}^2/\text{s)} \quad (4)$$

$$k_s = 0.0119 \text{ (cm}^2/\text{s)} \quad (5)$$

where, D_0 : initial particle size of PC (cm)
 k_g : gaseous combustion rate (cm²/s)
 k_s : solid combustion rate (cm²/s)
 M : weight of PC (g)

t_g : gaseous combustion time (s)
 t_s : solid combustion time (s)
 ρ : density of PC (g/cm^3).

On the other hand, D. A. Frank Kamenetskii⁷⁾ have confirmed that ignition delay time is dependent only on temperature and derived the following equation from the unsteady heat balance regarding heat generation, radiation and heat accumulation:

$$t_d = \frac{C_p \cdot \rho_g}{Q} \cdot \frac{R \cdot T_a^2}{E} \cdot \frac{1}{Z} e^{E/RT_a} \quad \text{.....(6)}$$

where, C_p : specific heat ($\text{kcal/kg} \cdot ^\circ\text{C}$)
 E : activation energy (kcal/mol)
 Q : heat of reaction (kcal/kg)
 R : gas constant ($\text{kcal/mol} \cdot ^\circ\text{C}$)
 t_d : ignition delay time (s)
 T_a : temperature ($^\circ\text{C}$)
 Z : constant (—)
 ρ_g : gas density (kg/m^3).

Substitution of physical-property into Eq. (6) and calculation by using the experimental results led to the Z value to be of 5.05.

When Eqs. (4) and (5) are applied, the resultant combustion time of -200 mesh (74×10^{-3} mm) PC is,

$$t_g = (74 \times 10^{-4})^2 / 0.0536 = 1.02 \times 10^{-3} \quad \text{.....(7)}$$

$$t_s = (74 \times 10^{-4})^2 / 0.0119 = 4.60 \times 10^{-3} \quad \text{.....(8)}$$

This shows that the combustion is completed in the order of 10^{-3} s.

Fig. 4 suggests that PC injected through the tuyeres is first heated up by the blast, followed by combustion. The residence time of PC in the raceway, on the other hand, is only from 10 to 30 ms. This means combustion seems to be completed in the raceway from the viewpoint of velocity. Taking the ignition delay before gaseous combustion into account, however, the probability for PC to go out of the raceway before solid combustion may be possibly high.

Takeda *et al.*³⁾ investigated the combustion of PC in a blast furnace by using a tuyere probe inserted from the sidewall and reported that the char was sampled out of the raceway as an unburnt material. Deguchi *et al.*⁴⁾, moreover, performed a series of experiments in which PC was injected into a combustion test furnace and found out that a part of PC remained unburnt in the raceway accumulating in the furnace. As the studies of coke-filled furnaces⁸⁾ the combustion rate of PC becomes higher with the enrichment of

Fig. 4. Conditions of coal injection at tuyere and that of unburnt pulverized coal during ascent.

oxygen. However, even if PC is injected into an actual blast furnace, combustion efficiency of PC will be at most 90 % in despite of the oxygen enrichment and 10 % of unburnt PC will inevitably flow out from the raceway and move upward in the furnace.

3.2. Remaining Position and Amount of Unburnt Pulverized Coal

Fig. 5 shows the change of the amount of residual fines in the coke-packed bed as a function of the time when the devolatilised PC is blown into the packed bed at room temperature and suggests that the amount of residual fines in the packed bed increases nearly in proportion to the time. Therefore, the slope of the line means residing rate of fines. Its relation with blowing conditions was examined and the results are shown in Fig. 6. When the experimental conditions

Fig. 5. Change of residual unburnt pulverized coal with time.

Fig. 6. Effects of gas flow rate, injection rate and sample kind on residual rate of unburnt pulverized coal.

Fig. 7. Change of amount of residual unburnt pulverized coal in a hypothetical blast furnace.

are fixed, there exists little difference between the amounts of residual fines in the sinter bed and the coke bed. Low gas velocities increase the amount of residual fines and this is remarkable in the lower gas velocity range. It is natural, of course, that the increased blowing amount should make the residual fines greater.

In the case of the coke packed bed, little difference was observed in the amount of residual fines between in the hot and cold states. In the case of sinter packed bed, on the other hand, high temperatures give rise to its softening, contraction and dripping to change the amount of residual fines remarkably more. Fig. 7 shows the longitudinal distribution of amount of residual fines to the height of a hypothetical blast furnace. The unburnt PC generated in the raceway goes up with the gas flow and its amount in the fused zone increases rapidly. The amount of unburnt PC collected at about 1400°C zone is maximum, decreasing gradually as the temperature decreases further. This may be because of the decreased contraction ratio and the increased void ratio. Although the retention of unburnt PC is not observed in the lumpy zone corresponding to 600–800°C zone, the fines of unburnt PC begin to reside again due to the decrease in gas flow rate.

3.3. Effect of Unburnt Pulverized Coal on High-temperature Properties of Sinter

Fig. 8 shows the temperature dependence of the pressure drop. There are several obvious steps in the softening and fusion process. The first step relates to initial fusion occurring at about 1100°C, where indirect reduction proceeds. The amount of the molten slag increases as the temperature rises and it tends to fill the voids, resulting in a rapid increase in the pressure drop. The subsequent step concerns direct reduction which changes FeO-rich slag to little or no FeO slag or to a metal. As the direct reduction proceeds, the amount of molten slag decreases and the permeability gradually increases. In this step, high-

Fig. 8. Change of pressure drop.

Fig. 9. Effect of temperature of unburnt pulverized coal injection on pressure drop.

fluidity slag containing FeO begins to drip.

Fig. 8 indicates that pressure drop in the softening and fusion zone corresponding to 1200–1400°C becomes small when the unburnt PC is injected into the furnace. This suggests that the unburnt PC is consumed by the direct reduction of FeO to make the amount of molten slag less and softening resistance more since the difference of pressure drop becomes greater with the increasing injection temperature as shown in Fig. 9.

During the softening and melting processes, two kinds of slag, high-FeO and low-FeO slag, are produced. The former has sufficient fluidity, while the latter becomes a residual slag which makes the metal dripping. Fig. 10 shows the effects of the injected unburnt PC on the relations between the melting down temperatures and the basicity. In both cases, the

Fig. 10. Change of melting down properties.

melting down temperature rises with the increasing basicity and the curve shifts upward when the unburnt PC is injected. In addition, the effect of the injected unburnt PC tends to be smaller with the increasing basicity. Thus, the presence of the unburnt PC has a strong effects on the melting down properties.

The change in the relative proportions of the dripped solid and the residual slag with temperature was calculated on the basis of the phase diagram of the multicomponent slags.⁹⁾ It is evident that the proportion of the solid in the residual slag is generally higher than that in the dripped slag.

The presence of the unburnt PC strongly affects the dripping properties of the metal. The unburnt PC reacts with the FeO-rich slag and decrease the amount of FeO changing the proportions of solid and liquid and then its fluidity. The reaction makes the high-viscosity slag and it shields the metal from coke effectively preventing the metal from carburization and melting down.

The unburnt PC may change the carbon concentration in the metal and the slag composition. Fig. 11 shows the carbon concentration in the dripped metal plotted in the Fe-C equilibrium diagram. The carbon in the metal increases as the temperature rises and helps the reduction. When the carbon concentration of the metal reaches that of the solidus of austenite, the metal begins to melt. In this experiment, it begins to drop at 100–150°C higher temperatures than the solidus of austenite. In the presence of unburnt PC the same behavior is seen as that without unburnt PC in the phase diagram. If the beginning temperatures of melting down are equal, the carbon concentration in the presence of unburnt PC coincides with that without unburnt PC.

Fig. 12 shows the slag compositions before the experiments and that in the sample layer after the experiments with or without the unburnt PC. When the unburnt PC is injected, the concentrations of CaO, SiO₂ and Al₂O₃ increase slightly, resulting possibly from the ashes. On the other hand, the concentration of FeO decreases remarkably. Since no change in the carbon concentration in the metal is observed, these facts prove that the unburnt PC is consumed selectively by the direct reduction of FeO.

4. Conclusion

In order to clarify the combustion reaction when PC is injected into the tuyeres of a blast furnace and

Fig. 11. Relation between melting down temperature and carbon content.

Fig. 12. Change of slag components.

the effects of the resultant unburnt PC on in-furnace reactions, some basic experiments were carried out and the following have been found.

(1) Most of PC injected through the tuyeres burns rapidly in the raceway but a part of PC is carried away out of the raceway without burning.

(2) The unburnt PC tends to stay in the softened and fused ore bed. The unburnt PC adhering to the ore bed is consumed by the direct reduction of FeO and improves effectively the high-temperature properties of the ore.

In this way, even when PC injected into the blast

furnace does not burn completely, it was found that is consumed effectively.

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