Influence of Two-Stage Air Injection Conditions on NO_x and Unburned Carbon of Sub-Bituminous Coal Combustion*

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Because of large recoverable reserves, sub-bituminous coal is an important energy resources. The disadvantage of sub-bituminous coal is that it contains more than 20% moisture. This makes ignition less efficient. And combustion flame became diffused. Both emissions of NO_x and unburned carbon in fly ash become high. We have already shown that these emissions can be reduced by adjusting the air injection conditions from the burner to better suit sub-bituminous coal combustion. However, the reduction is insufficient compared with bituminous coal combustion. In this investigation, influence of two-stage air injection conditions on NO_x and unburned carbon concentration in fly ash was studied and the optimum air injection conditions necessary in order to reduce those emissions were clarified.

Key Words: Sub-Bituminous Coal, Pulverized Coal Combustion, NO_x , Unburned Carbon, Two-Stage Combustion

1. Introduction

Coal is an important energy for meeting the increasing demand for electricity because there are more abundant coal reserves than those of other fossil fuels. At present, the main method of coal utilization in Japan is pulverized coal combustion of bituminous coal. However, considering the security of fuel supply and fuel cost, in the future it will be necessary to use lower rank coals, which contain higher moisture and have lower calorific values than bituminous coal⁽¹⁾. Low rank coal with moisture content higher than 20% is called sub-bituminous coal or lignite, and is mined in large amounts throughout the world⁽²⁾. Due to the 20–40% moisture content, sub-bituminous coal is difficult to ignite and NO_x emission is difficult to control.

We developed a low NO_x burner for bituminous coal^{(3),(4)}. The concept of this burner for NO_x reduction is shown in Fig. 1. A recirculation flow of combustion gas is produced near the burner. Part of the pulverized coal stays around the burner outlet for a long time because of the recirculation flow. Pulverized coal combustion is accelerated and temperature increases near the burner outlet.

Although NO_x formation becomes higher near the burner, NO_x is quickly decomposed into nitrogen in the intense and wide reduction flame. The unburned carbon concentration in the burning particle changes into gas components such as carbon monoxide near the burner outlet. The injection air of two-stage combustion fires these gas components. Therefore, the unburned carbon concentration in fly ash is lower than that when using a conventional burner.

We have already clarified combustion characteristics and emission of both NO_x and unburned carbon in fly ash of sub-bituminous coal⁽⁵⁾. It was found that the combustion flame of sub-bituminous coal became longer than that of bituminous coal. Furthermore, when the air injection conditions from the burner were controlled for sub-bituminous combustion, the emissions of both NO_x and

Fig. 1 Concept of low NO_x combustion

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unburned carbon in fly ash could be reduced. However, in that research, suitable air injection conditions for two-stage combustion were investigated for bituminous coal combustion⁽⁶⁾. However, the combustion flame of sub-bituminous coal became longer than that of bituminous coal combustion. Therefore, suitable air injection conditions of two-stage combustion for sub-bituminous coal are considered to be different.

In this study, the influence of air injection conditions of two-stage combustion on emission characteristics of NO_x and unburned carbon was investigated, and the optimum air injection conditions were clarified using a pulverized coal combustion test furnace.

Nomenclature

- A : Amount of primary air [kg/h]
 A/C : Mass ratio of primary air to pulverized coal [—]
 C : Coal feed rate [kg/h]
 C_r : Mass ratio of moisture remaining in the coal to that in dry coal [kg- H_2O /kg-dry coal]
 D : Diameter of the furnace (0.85) [m]
 L : Distance of the air injection port from the burner [m]
 S_s : Swirl vane angle of secondary air [deg]
 U_c : Unburned carbon concentration in fly ash [%]

2. Test Facility and Experimental Method

2.1 Test facility

Figure 2 shows a schematic of the coal combustion test furnace. The test furnace comprised a water-cooled, horizontal cylinder made of steel. The inner diameter of this furnace was 0.85 m and the length was 8 m. Refractory materials were placed on the inside walls of the furnace, with a thickness of 0.075 m. Combustion test conditions are shown in Table 1. Coal was supplied by table feeders fixed under each storage bin. The standard thermal input of supplied coal is 760 kW. Combustion air was

supplied from a forced draft fan and was divided into primary air and other combustion air. The temperature of primary air was set to 80°C and that of secondary and tertiary air was controlled at 350°C using air heaters and electric one. The primary air carried pulverized coal from the table feeders to the burner through a coal exhauster.

When sub-bituminous coal is pulverized, part of the moisture remains in the coal and the rest is vaporized. In this study, wet raw coal was pulverized and dried by air in the pulverizer. The moisture content remaining in the coal was almost the same value as the equilibrium moisture at room temperature and 75% relative humidity.

Secondary and tertiary combustion air were fed into the furnace via a wind box. In two-stage combustion, part of the combustion air is divided before the wind box and is injected at the side ports of the furnace. Fourteen air injection ports for two-stage combustion were mounted in

Table 1 Coal combustion test condition of the burner

Item	Adaro	Wara
Thermal input	760kW	
Air / Coal	2.2	
Temperature of primary air	80°C	
Swirl vane angle of secondary air	72deg	54deg
Swirl vane angle of tertiary air	72deg	72deg
Temperature of secondary and tertiary air	350°C	
Air ratio	1.24	
Temperature of injection air for two-stage combustion	350°C

Fig. 2 Schematic of coal combustion test furnace

the axial direction. The separation distance between each pair of neighboring ports was 0.4 m. Air for two-stage combustion was injected from the 6 ports in the cross section of the furnace shown in Fig. 2 (b). These 6 ports were mounted at same intervals of 60 deg around the furnace. The air injection point and ratio for two-stage combustion were variable in this facility.

Figure 3 shows the structure of the burner. This burner was an advanced low NO_x burner, a CI- α burner developed by CRIEPI and IHI (Ishikawajima-Harima Heavy Industries Co., Ltd.)^{(3), (4)}. The primary air nozzle is straight. The swirl forces of secondary and tertiary combustion air can be controlled independently.

2.2 Experimental method and measurement

In the experiment, the furnace was warmed by kerosene combustion before the pulverized coal combustion. After warming the furnace sufficiently, the fuel was gradually shifted from kerosene to coal. The value of thermal input in the coal combustion test furnace was 760 kW. The air ratio was 1.24. The mass ratio of primary air to pulverized coal, Air/Coal (A/C), was 2.2 and the mass ratio of secondary air to tertiary air was 0.167. When the temperature of the combustion air and exhaust gas became constant, the measurement for the experiment was started.

The gas components measured during the experiment were NO_x and O_2 at the exit of the furnace. The concentration of these gas components was also measured in the furnace. Gas temperature in the furnace was measured with a Pt/Pt-Rh (13%) sheath thermocouple and other points under 800°C were measured with a K-type thermocouple. Fly ash was collected in the gas cooler, the multi-cyclone and the bag filter. In this study, the unburned carbon concentration was determined as follows, by the measurement method of carbon content defined in JIS (Japanese Industrial Standards). The fly ash collected in each unit was heated to 815°C in the electrically heated furnace and the

unburned carbon concentration in each fly ash was calculated from the weight loss due to heating. The weight of fly ash was measured, and the overall value of the unburned carbon concentration in fly ash was determined as the weighted mean concentration of fly ash collected in each unit.

3. Tested Coal Properties

Table 2 shows the tested coal properties of Adaro and Wara, which are sub-bituminous coals mined in Indonesia. The moisture content of Adaro is about 20% and that of Wara is comparatively high at about 40%.

When sub-bituminous coal is pulverized by a mill, part of the moisture remains in the coal while the rest is vaporized. In this study, C_r is defined as the mass ratio of the remaining moisture to dry coal. The C_r values of Adaro and Wara are 0.24 and 0.73 respectively.

4. Results and Discussion

Although two-stage combustion has an effect on NO_x reduction, unburned carbon concentration in fly ash increases because of low air ratio combustion near the burner. It is necessary to optimize the air injection condition of two-stage combustion from the aspect of simultaneous reduction of both NO_x and unburned carbon.

4.1 Influence of air injection point of two-stage combustion on NO_x and unburned carbon

Figure 4 shows the influence of the distance of the air injection point in two-stage combustion from the burner, L/D , on emissions of NO_x and unburned carbon in fly ash during the combustion of the two kinds of sub-bituminous coal. L/D is defined as the distance divided by the diameter of the furnace. The swirl vane angle was fixed at the optimum value for sub-bituminous coal⁽⁵⁾. NO_x emissions are different between the two coals because of the differ-

Fig. 3 Structure of CI- α burner

Table 2 Tested coal properties

			Adaro	Wara
Proximate analysis	Moisture ^{*1}	[%]	19.5	42.1
	Ash ^{*2}	[%]	1.2	1.3
	Volatile matter ^{*2}	[%]	49.9	52.6
	Fixed carbon ^{*2}	[%]	48.9	46.1
Fuel ratio			0.98	0.88
Ultimate analysis ^{*2}	Carbon	[%]	71.3	68.1
	Hydrogen	[%]	5.7	5.5
	Nitrogen	[%]	1.25	1.06
	Oxygen	[%]	21.6	23.9
	Total sulfur	[%]	0.17	0.18
	Combustible sulfur	[%]	0.11	0.17
Calorific Value (High) ^{*1}			22.9	16.8
Calorific Value (Low) ^{*1}			21.3	15.1
Calorific Value (High) ^{*2}			28.4	28.1
Calorific Value (Low) ^{*2}			27.1	26.8

*1: Equilibrium moisture basis of coal at room temperature and 75% relative humidity

*2: Dry basis

Fig. 4 Influence of air injection point for two-stage combustion on emissions of NO_x and unburned carbon in fly ash

ence in their properties such as nitrogen and moisture content. When the air injection point was shifted downstream in the furnace, NO_x concentration at the exit of the furnace decreased. The effect of NO_x reduction worsened beyond an L/D distance of 4.5. On the other hand, the unburned carbon concentration in fly ash increased when the air injection point was shifted downstream in the furnace. The tendency of increase of the unburned carbon concentration became much higher after the same 4.5 L/D distance.

Figure 5 shows the distributions of temperature and oxygen and NO_x concentrations at the center axis in the furnace with L/D distances of 3.5, 4.5 and 5.4. The temperature in the furnace increased rapidly at the burner outlet and then began to a decrease toward the exit of the furnace under all conditions. Even the air injection point was changed, the temperature distribution in the furnace was almost the same under the three conditions. On the other hand, the consumption of oxygen progressed gradually away from the burner outlet and a reduction area was formed between the burner outlet and the air injection point for two-stage combustion. This area became wider as the air injection point shifted to the exit of the furnace. NO_x reduction was changed as follows. Much NO_x was formed at the burner outlet. However, NO_x was immediately reduced in the reduction area. When the air injection point was shifted to the exit of the furnace, the reduction area was wide and the NO_x concentration became lower at the exit of the furnace. Under this condition, unburned carbon concentration in fly ash became high. In particular, this tendency progressed as the injection point was shifted downstream in the furnace.

When the air injection point for two-stage combustion shifted towards the exit of the furnace, NO_x emission decreased and unburned carbon concentration in fly ash increased. This tendency of NO_x reduction become saturated as the air injection point for two-stage combustion shifted farther from the burner, and then unburned carbon

Fig. 5 Distribution of temperature, oxygen and NO_x concentration at the center axis in the furnace in the case of an air injection point distance of 3.5, 4.5 and 5.4

concentration in fly ash increased rapidly. From the viewpoints of the reduction of NO_x emission without the rapid increase of unburned carbon concentration in fly ash, the suitable air injection point was considered to be L/D of 4.5 during sub-bituminous coal combustion, this value is larger than the suitable point for bituminous coal combustion, which is L/D of 3.5 during bituminous coal combustion.

Although the optimum air injection point was found to be L/D of 3.5 for bituminous coal combustion, that point was shifted to 4.5 for sub-bituminous coal combustion. The reason for this difference was the delay of oxygen consumption due to the latent heat of the evaporation of moisture in the sub-bituminous coal and the decrease of partial oxygen pressure around coal particles caused by the existence of vaporized moisture. Therefore, the optimum air injection point for two-stage combustion was shifted to the exit of the furnace.

4.2 Influence of air injection ratio of two-stage combustion on NO_x and unburned carbon

The influence of the air injection ratio of two-stage combustion on the emissions of NO_x and unburned carbon in fly ash was investigated with the air injection point for two-stage combustion fixed at the injection point of

4.5. Figure 6 shows the relationship between air injection ratio for two-stage combustion and emissions of NO_x and unburned carbon in fly ash. When the air injection ratio increased, NO_x concentration at the exit of the furnace decreased. The effect of NO_x reduction tended to be saturated with an air injection ratio over 30%.

On the other hand, the unburned carbon concentration in fly ash became high when the air injection ratio increased. The unburned carbon concentration was highest with an air injection ratio of 40%. The unburned carbon concentration with an air injection ratio of 30% was almost the same as that in the case of 20%. The reason for this was considered by measuring temperature and gas concentration distributions in the furnace. Figures 7 and 8 respectively show the distributions of oxygen and NO_x concentrations in the furnace when the air injection ratio for two-stage combustion was fixed at 20% and 30% at the injection point of 4.5. When the air injection ratio was fixed at 20%, an area of low oxygen concentration was formed at the outer side in the furnace. Much NO_x was also formed at the outer side in the furnace. Under this condition, because the amounts of secondary and tertiary air of the burner were larger than those with an air injection ratio of 30%, the swirl force was intensive and

Fig. 6 Influence of air injection ratio for two-stage combustion on emissions of NO_x and unburned carbon in fly ash

Fig. 7 Distribution of oxygen concentration in the furnace in the case of two kinds of air injection ratios for two-stage combustion (Wara coal)

coal particles moved to the outer side in the furnace since sub-bituminous coal is fine and has a low density. Therefore, sub-bituminous coal was not fired efficiently at the combustion accelerating area under an air injection ratio of 20%. Also NO_x formation and decomposition were delayed, so NO_x concentration at the exit of the furnace became higher.

As a result, the air injection condition for two-stage combustion suitable for sub-bituminous coal was an injection point at an L/D distance of 4.5 with an injection ratio of 30%.

4.3 Reduction effect of NO_x and unburned carbon by optimization of air injection conditions

It was already clarified that NO_x emission was reduced when A/C was decreased and the air injection point for two-stage combustion was fixed at an L/D of 3.5⁽⁵⁾. Figure 9 shows the relationship between A/C and NO_x concentration at the exit of the furnace when the air injection

Fig. 8 Distribution of NO_x concentration in the furnace in the case of two kinds of air injection ratios for two-stage combustion (Wara coal)

Fig. 9 Relation between A/C and NO_x concentration at the exit of the furnace when the air injection point was fixed at an L/D of 3.5 and 4.5

Fig. 10 Effect of the air injection point for two-stage combustion on NO_x and unburned carbon concentration in fly ash (Estimated value of unburned carbon concentration in utility boiler calculated from that in test furnace)

tion point was fixed at 3.5 and 4.5. When A/C decreased, oxygen consumption was accelerated and the NO_x reduction area became wider. As a result, NO_x concentration at the exit of the furnace was reduced under both air injection conditions.

Figure 10 shows the effect of air injection conditions of two-stage combustion on emissions of NO_x and unburned carbon in fly ash. It was clarified that NO_x emission was much lower when the air injection condition for two-stage combustion was suitable for sub-bituminous coal combustion. Then, unburned carbon concentration had almost the same value as that in the air injection condition for bituminous coal combustion. By adjusting the burner and two-stage combustion conditions, emissions of both NO_x and unburned carbon were reduced to almost the same values as those of bituminous coal combustion.

5. Conclusion

In this study, the optimum air injection conditions to reduce the emissions of both NO_x and unburned carbon in fly ash during two-stage combustion were investigated. The main results can be summarized as follows.

1. When the air injection point for two-stage combustion was shifted downstream in the furnace, NO_x concentration at the exit of the furnace decreased due to the increase of the NO_x reduction area from the burner outlet to the air injection point in two-stage combustion. The effect of NO_x reduction tended to be saturated beyond an L/D distance of 4.5 from the burner outlet.

On the other hand, the unburned carbon concentration in fly ash increased when the air injection point for two-

stage combustion was shifted downstream in the furnace. In particular, the unburned carbon concentration tended to increase considerably after an L/D of 4.5. Therefore, the optimum injection point was shifted to the exit of the furnace because a large NO_x reduction area was required for sub-bituminous coal combustion as compared with bituminous coal combustion.

2. NO_x concentration at the exit of the furnace decreased with an increase of the air injection ratio, but saturated with an air injection ratio of over 30%. On the other hand, the unburned carbon concentration in fly ash increased with an increase of the air injection ratio up to 20%, whereas the ratio at 30% was almost the same as that at 20%. When the air injection ratio was higher than 30%, the unburned carbon concentration increased sufficiently. Therefore, the optimum air injection ratio for two-stage combustion of sub-bituminous coal is 30%.

3. When the air injection conditions for both the burner and two-stage combustion were optimized for sub-bituminous coal, the emissions of NO_x and unburned carbon in fly ash with sub-bituminous coal combustion were much lower than those under the air injection condition optimized for bituminous coal combustion. Under the optimized condition for sub-bituminous coal combustion, the emissions of NO_x and unburned carbon had almost the same values as those for bituminous coal combustion.

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