Emission Characteristics of NO_x and Unburned Carbon in Fly Ash of Sub-bituminous Coal Combustion*

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Sub-bituminous coal is considered to be one substitute fuel for bituminous coal. Since sub-bituminous coal contains more than 20% moisture, there are some problems with its utilization, such as a decrease in combustibility, high NO_x emission and so on. This report describes the emission characteristics of NO_x and unburned carbon in fly ash of sub-bituminous coal combustion through the use of a pulverized coal combustion test furnace. On the sub-bituminous coal combustion, ignition at the burner exit worsened and the combustion flame became diffused. Then, both NO_x emission and the unburned carbon concentration in fly ash became high. In order to keep stable combustion and to form an effective NO_x reduction flame, the swirl vane angle of secondary air was reduced and the Air/Coal ratio was lowered. As a result, the combustion flame became moderate, and both NO_x emission and unburned carbon concentration in fly ash could be reduced.

Key Words: Sub-bituminous Coal, Pulverized Coal Combustion, Low NO_x Burner, Unburned Carbon Concentration in Fly Ash

1. Introduction

Coal is an important energy resource to meet the future demand for increasing electricity because it has more abundant reserves than those of other fossil fuels. At present, the main method of coal combustion is pulverized coal combustion with bituminous coal. However, from the viewpoints of fuel security and fuel cost, in the future it will become necessary to use lower rank coals, which are richer in moisture or ash and have lower calorific values than bituminous

coal⁽¹⁾. Although the bituminous coal usually fired in thermal power stations in Japan contains under 5 wt% moisture⁽²⁾, low rank coal containing higher than 20 wt% moisture is mined in large amounts throughout the world⁽³⁾. The moisture content of sub-bituminous coal belongs between 20 and 40 wt%. Utilization of sub-bituminous coal has some problems, such as a decrease in combustibility, control of NO_x emission and so on. This paper describes the influence of such coal's moisture condition on combustion characteristics. This research was conducted using a pulverized coal combustion test furnace (coal combustion rate: 0.1 t/h). Furthermore, the influence of combustion air injection conditions on the emission of NO_x and unburned carbon in fly ash was investigated and the optimum injection condition for combustion air was studied. The most effective combustion condition for sub-bituminous coal in reducing the emission of the NO_x and unburned carbon in fly ash was clarified.

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Nomenclature

Air/Coal: Mass ratio of primary air to pulverized coal [—]

C_r : Mass ratio of remained moisture in coal to the coal on the dry basis [kg-H₂O/kg-dry coal]

C_v : Mass ratio of vaporized moisture to the coal on the dry basis [kg-H₂O/kg-dry coal]

C_t : Sum of C_r and C_v [—]

S_s : Swirl vane angle of secondary air [deg]

2. Test Facility and Experimental Method

2.1 Test facility

Figure 1 shows details of the test furnace. The test furnace was a water-cooled, horizontal and cylindrical type furnace, 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 at a thickness of 0.075 m. Coal was supplied by table feeders settled under each storage bin. The coal feed rate was about 100 kg/h. Combustion air was supplied from a forced draft fan and was divided into primary air and other combustion air. The temperature of the combustion air was kept constant by air heaters. The primary air carried coal from the table feeders to the burner through a coal exhauster.

When sub-bituminous coal is pulverized, part of moisture remains in the coal and part is vaporized. In this study, the influence of these moisture conditions on combustibility was investigated. The moisture content remaining in the coal was controlled by changing the temperature of the hot air in the pulverizer. The concentration of vaporized moisture in the primary air was controlled by supplying moisture vapor from the evaporator.

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

Fig. 1 Outline of coal combustion test furnace

for two-stage combustion were mounted on the furnace sidewall.

Figure 2 shows the structure of the burner. This burner was an advanced low NO_x burner, which is a CI- α burner developed by CRIEPI and IHI (Ishikawajima-Harima Heavy Industries Co., Ltd.)^{(4),(5)}. The primary air nozzle has a straight shape. The swirl force of secondary and tertiary combustion air can be controlled independently. When the swirl vane angle is high, swirl force increases. The concept of this burner for NO_x reduction is as follows. 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 this recirculation flow. Pulverized coal combustion is accelerated and temperature increases near the burner outlet. Though NO_x formation becomes higher near the burner, NO_x is quickly reduced to N₂ in the intensive and wide reduction flame. The unburned carbon in the coal changes to gas components such as carbon monoxide near the burner outlet. These gas components are fired after the air for two-stage combustion is injected. Therefore, the unburned carbon concentration in fly ash is lower than that of a conventional burner.

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 7.60×10^2 kW. The air ratio was 1.24. The mass ratio of the primary air to the pulverized coal (*Air/Coal*) was 2.2, and the mass ratio of the secondary air to the tertiary air was 1 : 6.

Fig. 2 Structure of CI- α burner

In two-stage combustion, the mass ratio of the staged air to the total one was fixed at 30%. The distance from the burner outlet to the injection port for two-stage combustion air was settled at 2.99 m. 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 , O_2 and CO at the exit of furnace. The gas 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 the other points under 800°C were measured with a CA-type thermocouple. Fly ash was collected in the gas cooler, the multi-cyclone and the bag filter. The weight of fly ash collected in each facility was measured and the unburned carbon concentration in fly ash was determined by measurement of the weight loss heated to $800 \pm 10^\circ\text{C}$ in the electrically heated furnace. The overall value of unburned carbon concentration in fly ash was calculated as the weighted mean value of that in each facility.

3. Tested Coal Properties

Table 1 shows the tested coal properties of Newlands and Wara coal. Newlands coal is bituminous coal from Australia. In this study, this coal is used to compare combustion characteristics with sub-bituminous coal. Wara coal is a sub-bituminous coal from Indonesia. The moisture content of this coal is about 40%, much higher than that of the ordinary coal fired in the thermal power stations in Japan. The mean diameter of the pulverized coal was $40\text{ }\mu\text{m}$.

When sub-bituminous coal is pulverized with the mill, part of the moisture remains in the coal and part is vaporized. In this paper, to clarify the influence of moisture conditions on combustion characteristics,

three levels of the remaining moisture content in the coal (C_r) were used, namely 0.20, 0.30 and 0.67 [$\text{kg-H}_2\text{O/kg-dry coal}$].

4. Results and Discussion

4.1 Combustion characteristics of sub-bituminous coal with the combustion air injection conditions optimized for bituminous coal

Coal combustion characteristics of the three levels of coal moisture content were evaluated with the combustion air injection conditions optimized for bituminous coal. Figure 3 shows the distribution of the oxygen concentration in the furnace for Newlands and Wara coal combustion. When the Newlands coal was fired, the combustion flame was stable. The consumption of oxygen progressed gradually from the burner outlet. The reduction area between the burner outlet and the injection port for two-stage combustion air was widely formed in the furnace. Distribution of the oxygen concentration for Wara coal combustion was then compared under the three levels of remaining moisture content. The total moisture content in the coal (C_t), meaning the sum of the vaporized moisture content (C_v) and C_r , that was supplied in the primary air was equal to 0.67. C_v was the mass ratio of vaporized moisture to the coal on a dry basis. When C_r increased, the ignition worsened and the combustion flame became diffused, so that the reduction region was decreased. It was considered that the reason for the delay of oxygen consumption was that the latent heat of evaporation increased.

Figure 4 shows the distribution of the NO_x concentration at the center axis in the furnace. When bituminous coal was fired, NO_x was formed rapidly at the burner exit. However, NO_x was immediately reduced at the reduction area between the burner outlet and the air injection port for two-stage

Table 1 Tested coal properties

			Newlands	Wara
Proximate analysis	Moisture ^{*1}	[%]	2.5	41.2
	Ash ^{*2}	[%]	15.2	2.1
	Volatile matter ^{*2}	[%]	28.4	51.4
	Fixed carbon ^{*2}	[%]	56.4	46.5
		Fuel ratio	[-]	0.90
Ultimate analysis ^{*2}	Carbon	[%]	71.8	67.0
	Hydrogen	[%]	4.5	5.2
	Nitrogen	[%]	1.59	1.21
	Oxygen	[%]	6.40	23.90
	Total sulfur	[%]	0.54	0.64
	Combustible sulfur	[%]	0.48	0.63
		Calorific Value (High) ^{*2}	29.1	27.0
		Calorific Value (Low) ^{*2}	28.1	25.9

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

*2 : Dry basis

Fig. 3 O_2 concentration in the furnace in the case of combustion air injection conditions optimized for bituminous coal

Fig. 4 Influence of the remaining moisture content in coal on NO_x concentration in the center axis of the furnace

Fig. 5 Relation between the swirl vane angle of secondary air and NO_x concentration at the exit of the furnace

combustion. In the case of sub-bituminous coal combustion, NO_x formation and decomposition were delayed. When Cr increased, NO_x formation was delayed and decomposition of NO_x at the reduction area decreased because of the worsening of combustibility. Therefore, NO_x concentration at the exit of the furnace increased as the remaining moisture content in coal became higher.

4.2 Adjustment of combustion air injection conditions for sub-bituminous coal

Since NO_x concentration at the exit of the furnace was high in the case of combustion air injection optimized for bituminous coal, the volume and the swirl force of combustion air were controlled in order to improve combustion stability. The influence of the flow rate of secondary combustion air to the sum of secondary and tertiary combustion air on NO_x concentration at the exit of the furnace

Fig. 6 Relation between the swirl vane angle of secondary air and O_2 concentration in the furnace (C_r : 0.67)

indicated tendencies similar with bituminous coal combustion. The influence of the swirl vane angle of tertiary combustion air was also shown to have a similar tendency. On the other hand, the swirl vane angle of secondary air (S_s) had an effect on NO_x emission different from bituminous coal combustion. The influence of S_s on NO_x concentration is shown in Fig. 5. When bituminous coal was fired, the optimum S_s was about 80 deg. The intensive swirl force was suitable for bituminous coal. However, sub-bituminous coal had unstable combustion at the same S_s . When the S_s was between 50 and 60 deg, the NO_x concentration at the exit of the furnace was the minimum.

Figure 6 shows the distribution of oxygen at S_s of 81 deg and 54 deg in regards to sub-bituminous coal combustion. When the S_s was about 50 deg, the combustion of sub-bituminous coal was accelerated and the shape of the combustion flame seemed to be moderated because of the weak swirl flow. As a result, the concentration of pulverized coal near the burner became higher and the consumption of oxygen was accelerated. Therefore, the reduction area between the burner outlet and the injection port for two-stage combustion air became wider and NO_x was decomposed sufficiently.

To improve ignition conditions at the burner outlet, the influence of primary air volume on NO_x emission was investigated. Figure 7 shows the relation between Air/Coal and NO_x concentration at the exit of the furnace. When the mass of primary air decreased, the ignition was improved and NO_x concentration at the exit of the furnace became lower. If Air/Coal was over 2.2, the combustion flame was

Fig. 7 Relation between *Air/Coal* and NO_x concentration at the exit of the furnace

Key	Remained moisture in coal [-]	Vaporized moisture [-]	Air/Coal [-]	Ss [deg.]
○	0.20	0.47	2.2	81
●	0.20	0.47	2.2	72
△	0.30	0.37	2.2	81
▲	0.30	0.37	2.2	63
□	0.67	0.00	2.2	81
■	0.67	0.00	2.2	54
◆	0.67	0.00	1.9	54

Fig. 8 Influence of combustion air injection conditions on NO_x concentration and unburned carbon concentration in fly ash

blown out. If the *Air/Coal* was under 1.9, pulverized coal was precipitated in the primary air tube. It was found that NO_x concentration was lowest when the *Air/Coal* was 1.9. At that ratio, the NO_x concentration was reduced about 200 ppm.

4.3 Emission characteristics of NO_x and unburned carbon in fly ash

The emission characteristics of NO_x and unburned carbon concentration were compared with C_r of 0.20, 0.30 and 0.67, with the same C_t of 0.67. Figure 8 shows the influence of C_r on NO_x concentration at the exit of the furnace and the unburned carbon concentration in fly ash. When the Ss was optimized for sub-bituminous coal combustion, both NO_x concentration and the unburned

carbon concentration decreased. When C_r became lower, NO_x concentration decreased. When C_r was high, the effect of NO_x reduction became higher because ignition was improved considerably by adjusting the combustion air injection conditions. When the *Air/Coal* was 1.9, the emission of both NO_x and unburned carbon decreased further. It was clarified that the ratio of NO_x reduction was achieved about 40% with a C_r of 0.67. By optimizing the burner conditions or by reducing moisture content of coal, not only NO_x emission but also unburned carbon concentration could be reduced.

5. Conclusion

The emission characteristics of NO_x and unburned carbon in fly ash of sub-bituminous coal combustion were evaluated. Adjustment of the combustion air injection conditions to reduce the emission of NO_x and unburned carbon in fly ash was also investigated. The main results can be summarized as follows.

1) Since sub-bituminous coal includes much moisture, the ignition worsen and the combustion flame diffuses widely at the burner outlet under the injection conditions of the combustion air optimized for bituminous coal. When the ratio of the remaining moisture in the coal to the total amount of moisture was higher, the oxygen consumption was delayed and the diffusion of the combustion flame was large. Furthermore, the emission of both NO_x and the unburned carbon in fly ash became higher.

2) The control of the swirl vane angle of the secondary air could improve ignition. When the Ss was about 50 deg, the combustion flame became moderate and the ignition were improved at the burner outlet. NO_x concentration at the exit of furnace was reduced. The decrease of the volume of primary air improved ignition and the effect of NO_x reduction was higher. The reason for NO_x reduction was considered to be that the NO_x reduction region from the ignition position to the injection port for the two-stage combustion air had become wider.

3) When combustion air injection conditions were optimized for sub-bituminous coal combustion, both NO_x concentration at the exit of furnace and the unburned carbon concentration decreased. When C_r became lower, NO_x concentration at the exit of furnace decreased. When the C_r was higher, the effect of NO_x reduction became much higher because the ignition was improved considerably and the NO_x reduction region became wider. It was clarified that the ratio of NO_x reduction was achieved about 40% with a C_r of 0.67.

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References

- (1) Coal Information, (1994), IEA.
- (2) Coal Project, Project News (in Japanese), (1999).
- (3) Survey of Energy Resources 1998, 18th World Energy Council, (1998).
- (4) Makino, H. and Kimoto, M., Low NO_x Combustion Technology in Pulverized Coal Combustion, Kagaku Kogaku Ronbunshu, (in Japanese), Vol. 20, No. 6 (1994), pp. 747-757.
- (5) Makino, H., Kimoto, M., Kiga, T. and Endo, Y., Development of New Type Low NO_x Burner for Pulverized Coal Combustion, Karyoku Genshiryoku Hatsuden, (in Japanese), Vol. 48, No. 6 (1997), pp. 702-710.
- (6) Ikeda, M., Kozai, Y., Kimoto, M. and Makino, H., Study of Control NO_x Emission and Unburned Carbon Concentration in Fly Ash on the Sub-bituminous Coal Combustion, CRIEPI Report, (in Japanese), No. W97023 (1998).