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Characteristics of Pulverized Coal Combustion in High-Temperature Preheated Air

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The use of high-temperature, low oxygen-content air for pulverized coal combustion is presented. Laboratory-scale tests were conducted in a drop-tube furnace to confirm the performance of such a combustion system. The furnace wall was maintained at 1300°C by a ceramic heater, and the high-temperature preheated air (around 1000°C) was supplied by a regenerative burner. NOx formation and combustion efficiency of the furnace were measured for various air preheat temperature, excess-air ratio, and oxygen concentration in the air. Measurements indicated that increasing air preheat results in increased combustion efficiency and reduced NOx emission, whereas decreasing the oxygen content of the combustion air leads to large reduction in combustion efficiency, accompanied with a slight decrease or increase in NOx. It can be concluded from the test results that the use of high-temperature, diluted air is not suited for pulverized coal combustion.

Introduction

THE use of high-temperature air for combustion in industrial furnaces has many advantages, such as good flame stability, lower NOx emission, and uniform gas temperature profiles.[1] In these combustion systems, the combustion air is preheated to approximately 1000°C using regenerative burners [high cycle regenerative combustion system (HRS)], and injected into the furnace at high velocity along with the fuel. It is thought that the high-temperature air helps to stabilize the flames and that the high-velocity turbulent mixing of the fuel and oxidizer results in the low thermal NOx emission. This high-temperature air combustion technology, firing on gas or light oil, has been successfully used in many industrial applications.[2]

It would be attractive if this technology could also be applied to coal combustion, inasmuch as coal is one of the major energy resources in the world and will remain so in the foreseeable future. Direct combustion of pulverized coal in such a furnace is difficult because of the molten ash in the flue gas that will plug the heating elements of the regenerative burners. However, this problem can be circumvented by the use of heat exchangers, such as utilized in the present study, or by the use of duct burners, which allows one to take full advantage of the high-temperature combustion air. The question remains as to whether the fuel-bound nitrogen in the coal, being different from gaseous and liquid fuels, will affect the overall NOx emission and combustion efficiency of the furnace at combustion-air temperatures considerably higher than those encountered in conventional boilers. As for the effect of temperature on the NOx production, many researchers have pointed out that the NOx emissions decreased with temperature under fuel-rich conditions, but they increased under uncontrolled combustion.[3,4] However, they investigated the influence of furnace temperature, not that of air temperature. Combustion tests were carried out in a drop-tube furnace to address this question. The results of the tests are reported herein.

Experimental Apparatus

Figure 1 shows the arrangement of the experimental apparatus. The main components of the test facility are the drop-tube furnace and the HRS air preheater, whose sectional views are schematically shown in Figs. 2 and 3, respectively.

The drop-tube furnace is cylindrical in shape, consisting of an inner alumina tube, whose surface temperature can be controlled by the use of a ceramic heater. The inner dimension of the furnace is 200 mm in diameter and 2000 mm in length. Pulverized coal, 80–85% of which passed through 74-μm sieve, is supplied by a table feeder and injected into the furnace through a nozzle located at the top of the furnace, assisted by a small amount of air. Gas and particulate (char or fly ash) samplings are taken at various positions along the center axis of the furnace. Access for the sampling probes is through a port located at the bottom of the furnace. The sampling probes are cooled by hot water. Table 1 lists the gas species that were analyzed.

The high-temperature air preheater has a pair of combustion channels, each of which consisted of a liquefied petroleum gas burner and a honeycomb ceramic heat-storage bed. The heat-storage and heat-discharge functions of the storage beds alternate between the two combustion channels with a switching period of approximately 25 s. Figure 3 shows the instant that channel B is in the heat-storage mode and channel A is in the heat-discharge mode. Combustion takes place in channel B, and the resulting high-temperature combustion gas is used to heat up storage bed B. The flue gas exits at the bottom of the preheater. Simultaneously, heat is removed from storage bed A to preheat the air. High-temperature preheated air exits at the top of the preheater. The dimensions of the preheater are about 1.2 m in height and about 0.7 m in width. Additional details on the

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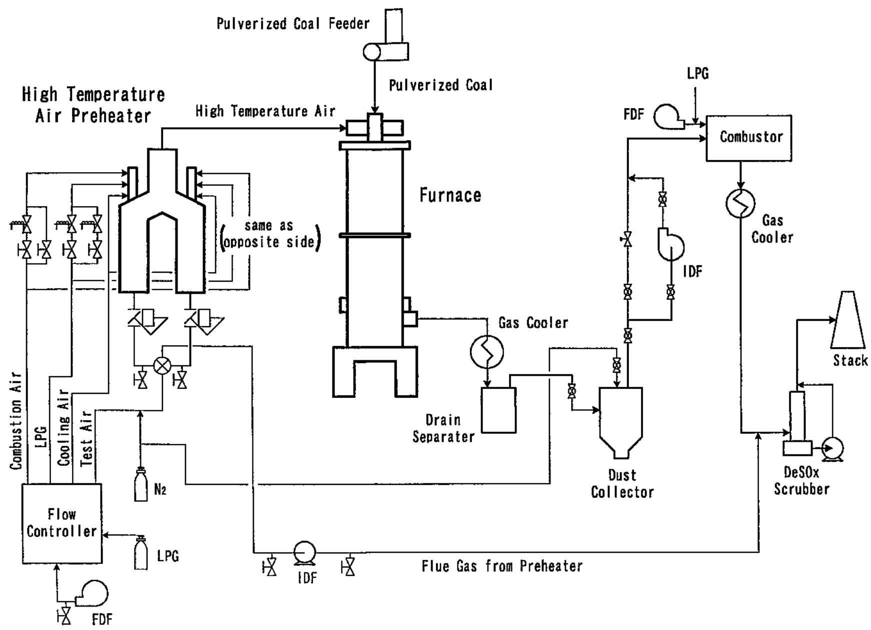

Fig. 1 Schematic of experimental apparatus.

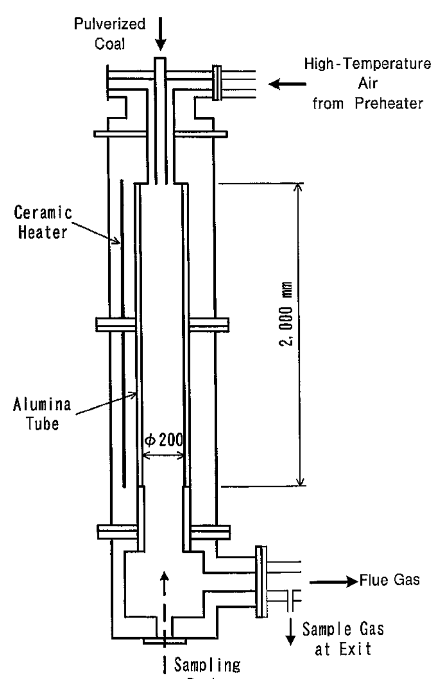

Fig. 2 Sectional view of the drop-tube furnace.

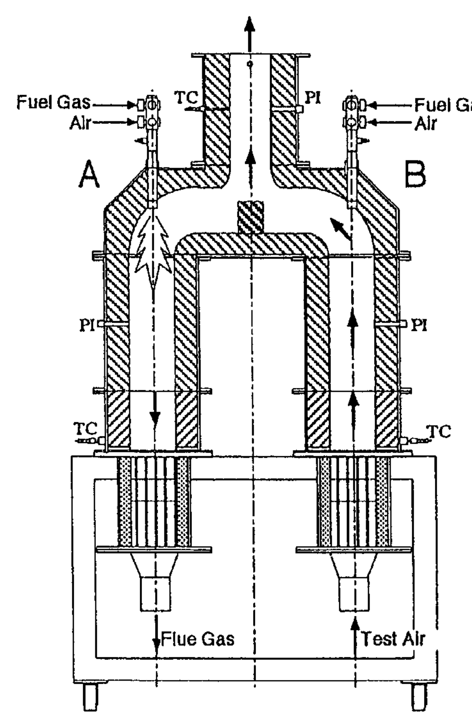

Fig. 3 Sectional view of high-temperature air preheater.

Table 1 Analyzed gas components

Components	Measures
O_2	Paramagnetic
NOx	Chemiluminescence (reducing pressure)
HCN	Colorimetric (batch)
NH_3	Colorimetric (batch)
CO	Nondispersion infrared absorption

design and operation of the HRS preheater may be found in Ref. 5. Variation of the oxygen content of the high-temperature combustion air is achieved during the experiment by mixing additional N_2 gas with air at the inlet of the air preheater.

Experimental Conditions

In the present experiments, the wall temperature of the furnace was controlled to be constant at 1300°C by use of a ceramic heater. Flow rate of the combustion air was kept constant at 26 kg/h for each condition to keep residence time in the furnace almost constant. Coal feed rate was almost 3 kg/h in the test in which oxygen concentration in combustion air was 21% and the excess-air ratio was 1.2. The conditions of lower oxygen concentration in combustion air were obtained by lowering coal feed rate in proportion to the oxygen flow rate. Under these conditions, temperatures and oxygen concentrations of combustion air were varied at two excess-air ratios of 1.2 and 1.0. Experimental conditions are summarized in Table 2. Coal tested in the present experiments is Australian bituminous coal, and its properties are summarized in Table 3.

Results and Discussion

Figure 4 shows the measured combustion efficiency and concentrations of NOx, HCN, NH_3, and O_2 along the axis of the furnace for three cases, cases 1, 3, and 5 (Table 2). In our experiment, the

Table 2 Experimental conditions[a]

Parameter	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Air temperature, °C	850	600	35	850	850	850	850	850
O_2 in combustion air, %	21	21	21	15	8	21	15	8
Excess-air ratio	1.2	1.2	1.2	1.2	1.2	1.0	1.0	1.0

[a]Furnace temperature 1300°C.

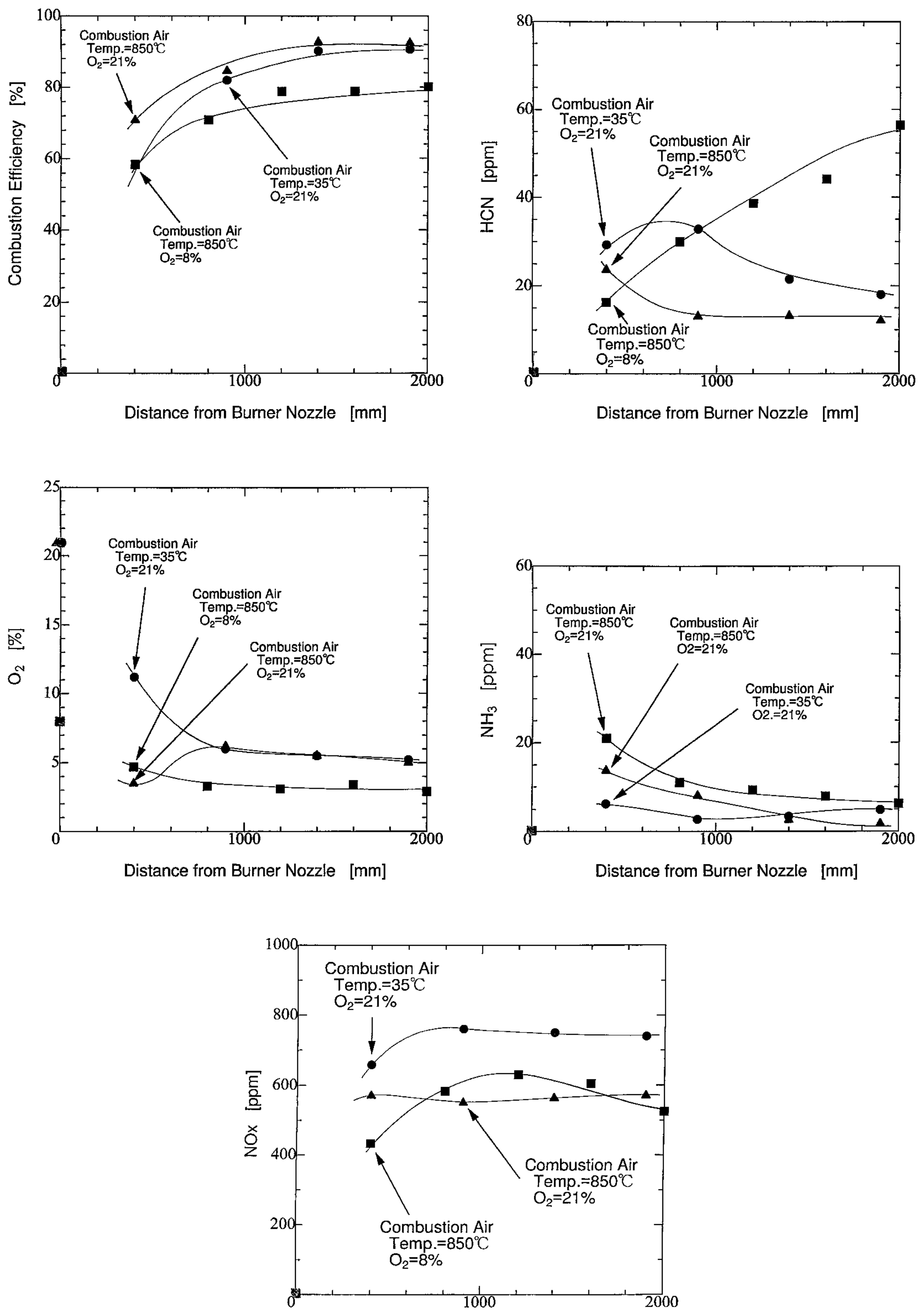

Fig. 4 Combustion efficiency and O_2, NOx, HCN, and NH_3 concentration along the axial direction in the furnace for cases 1, 3, and 5 (NOx, HCN, and NH_3 concentration for case 5 are converted to 21% oxygen condition).

concentrations of NOx, HCN, and NH_3 are diluted by nitrogen for those tests with low oxygen concentration in the combustion air. For this reason, the measured concentrations of these species have all been converted to the 21% oxygen condition. The combustion efficiency is calculated from unburnt carbon in sampled ash assuming that the amount of ash is constant during combustion.

Effect of Combustion Air Temperature

The effect of air preheat temperature on the combustion characteristics can be seen by comparing the results of cases 1 and 3 in Fig. 4. In case 1 (high-temperature air preheat), pulverized coal particles were heated rapidly, and the devolatilization and the combustion of the volatile matter were promoted at the early stage of combustion where the mixing of combustion air with pulverized coal was not sufficient. Accordingly, O_2 concentration in the flue gas was reduced greatly and rapidly. Nitrogenous species such as NH_3 and HCN were also released quickly and oxidized into NO, but they were reduced into molecular nitrogen under the atmosphere rich in gaseous hydrocarbon.

On the other hand, in case 3, the lower air-temperature condition, because the devolatilization and the combustion proceeded slowly, the oxygen in combustion air was not consumed so quickly as in case 1 resulting in lower burn out than in case 1. Nevertheless, the release rate of nitrogenous species was also smaller than in case 1; NOx emission was larger due to higher oxygen concentration in the region near the pulverized coal nozzle. NOx reduction can be seen in the latter part of the furnace through HCN and NH_3, and some amount remained as NH_3.

Figure 5 shows the NOx and total fixed nitrogen (TFN) concentrations and the combustion efficiency measured at the furnace outlet as a function of the air preheat temperature for nondiluted combustion air and for excess-air ratio of 1.2. TFN is defined as the total concentration of NOx, HCN, and NH_3. From the results, note that a major part of the nitrogenous species is contributed by NOx. It can also be seen that increasing the air preheat temperature results in decreased NOx emission and slightly improved burn out of the char.

Table 3 Test coal properties[a,b]

Property	Percentage, %
Proximate analysis	
Total moisture[c]	8.4
Moisture	3.3
Fixed carbon	53.0
Volatile matter	31.1
Ash	12.6
Ultimate analysis	
C	73.01
H	4.41
O	4.65
N	1.62
S	0.43

[a]Higher heating value 28.67 MJ/kg.
[b]Air-dried base.
[c]As received.

Effect of O_2 Concentration in Air

The effect of air dilution, or reduced O_2 concentration of the combustion air, on the combustion characteristics is obtained by comparing cases 1 and 5 in Fig. 4. It is noted from the profile of the combustion efficiency that the combustion proceeded very slowly due to lower oxygen concentration in the combustion air in spite of higher combustion air temperature. The status was same for nitrogenous species. That is, much of the NH_3 released during devolatilization near the pulverized-coal nozzle remained unoxidized, and NOx formation was not active in the early stage of the combustion. The highest value of NOx concentration was in the later part of the furnace, and then NOx was gradually decomposed.

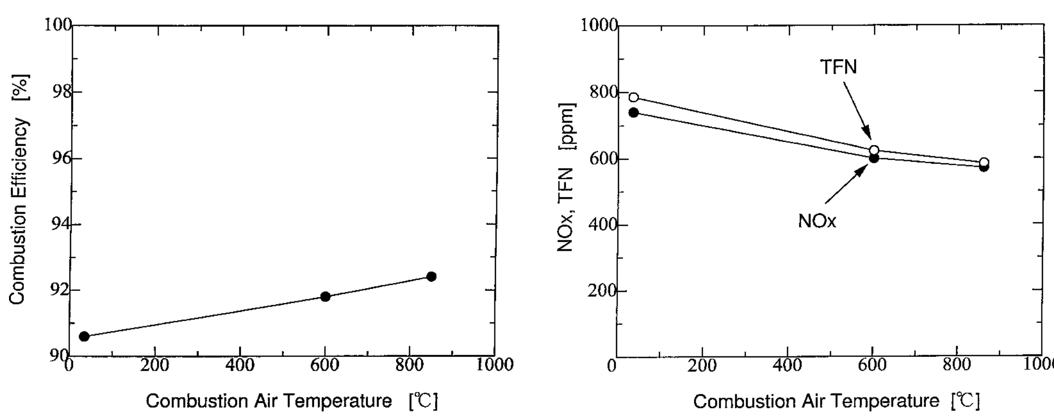

Fig. 5 NOx and TFN emissions and combustion efficiency vs combustion air temperature (O_2 concentration = 21%, excess = 1.2).

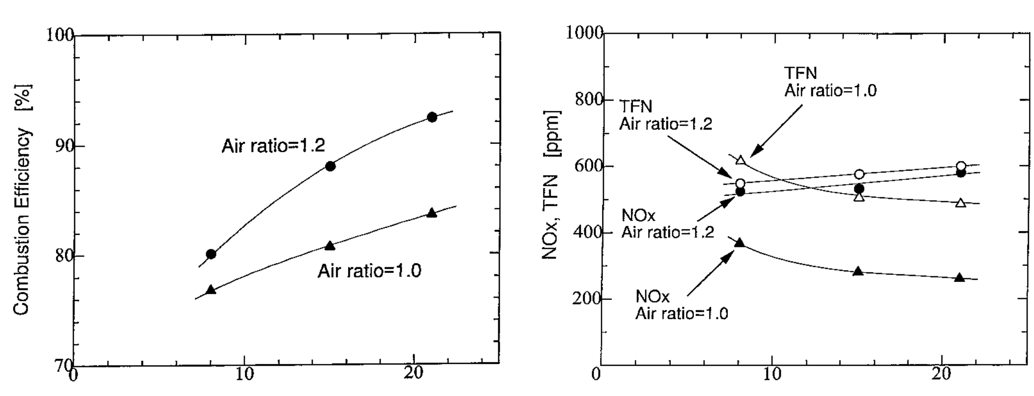

Fig. 6 NOx and TFN emissions and combustion efficiency vs oxygen concentration: (furnace temperature = 850°C; NOx, HCN, and NH_3 concentration are converted to 21% oxygen condition).

The release of HCN seemed to continue throughout the measured combustion process. Note that HCN produced from the reduction of NOx was accumulated without being decomposed into NH_3 or being oxidized into NO under the low oxygen condition.

In Fig. 6, the relation between NOx and TFN emission and oxygen concentration in combustion air is plotted. In the case of excess-air ratio of 1.2, HCN and NH_3 were not so dominant among nitrogenous species, and both NOx and TFN were slightly decreased with the lowering of the oxygen concentration in the combustion air. On the contrary, the combustion of pulverized coal was obviously restrained by lowering the oxygen concentration. The combustion efficiency will be somewhat improved in actual pulverized coal combustion with high temperature and low oxygen combustion air because the excess oxygen concentration in the flue gas will be set to the same value as in ordinary combustion.

Effect of Excess-Air Ratio

In Fig. 6, the data are also plotted for excess-air ratio of 1.0 simulating staged combustion. It is evident from Fig. 6 that about a half of the TFN was occupied by HCN and NH_3 under the condition of low excess-air ratio. Because HCN and NH_3 are easily oxidized into NOx during the complete combustion process in staged combustion, NOx emission should be evaluated by the amount of TFN. From Fig. 6, TFN emission increased with the lowering of the oxygen concentration in the combustion air. The reason is thought to be that the nitrogenous species remained without reacting because of the slow progress of combustion in the lower oxygen atmosphere, as is clear from the data for combustion efficiency. This means that the rapid devolatilization in staging will lead to lower emission of the TFN and also that the TFN will be less in the actual combustion system, where the flame temperature is higher than that in this study.[6]

Conclusions

Experiments were conducted to confirm the performance of pulverized coal combustion in high-temperature preheated air. Combustion characteristics were measured in a drop-tube furnace for various preheat temperatures, amounts of air dilution, and values of excess-air ratio. Relatively low furnace temperature was selected in the experiments to minimize thermal NOx formation. The following conclusions resulted.

1) Combustion using high-temperature air is useful for the elevation of combustion efficiency and the reduction of fuel NOx because a rapid devolatilization promotes the decomposition of nitrogenous species.

2) In the case of lowering the oxygen concentration of the combustion air, the combustion progresses slowly even if the temperature of the combustion air is high. As a result, the large NOx reduction obtained in the high-temperature air combustion using gas or light oil cannot be expected for pulverized coal, which contains organic nitrogen in it.

3) Under the condition of low excess-air ratio, such as staged combustion, high-temperature and low-oxygen combustion brings about not only the increase of NOx emission, but also the decrease of combustion efficiency because of the slow combustion rate.

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