Reduction of NO_x Emissions by Staged Combustion in a High Intensity Spray Combustor*

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NO_x reduction effects by staged spray combustion in a high intensity swirl combustor have been investigated using kerosene with a pyridine content of 0-1.7 %. The secondary air was radially injected into the combustion chamber through a multi-holed tube which was axially inserted from the rear side of a cylindrical combustor. Experiments have been carried out while varying the secondary air injection point, the primary to secondary air ratio, the pyridine content and the fuel flow rate. The main experimental results are as follows: (1) By effective mixing of a fine fuel spray with an air flow, with a large swirl degree, in the primary combustion zone, and by maintaining a suitable supply of secondary air, low NO_x emission can be realized even in a high intensity combustion state. (2) The secondary air supply at a point where the primary combustion is almost completed is effective for reducing NO_x emissions. (3) The primary to secondary air ratio for a suitably low NO_x emission has a tendency to increase with a decrease in combustion intensity.

Key Words: Spray Combustion, Staged Combustion, NO_x Emission, High Intensity Combustion, Swirl Combustor

1. Introduction

For various spray combustion equipment, like industrial boilers and manufacturing furnaces, various combustion methods such as low NO_x burner systems⁽²⁾ and single-⁽³⁾ and multi-staged⁽⁴⁾⁽⁵⁾ combustion methods have been proposed and utilized to reduce the NO_x emission. However as reducing measures are adopted, the general result is that the combustion intensity seems to be unfortunately decreased due to flame elongation.

A high intensity combustion is realized by obtaining a short flame combustion due to the rapid mixing of a fine fuel spray with air. However, in this case, it is generally indicated that the NO_x emission attains a high level because of the high temperature and O₂-rich flame formation.

The objective of this study is to provide various

conditions of spray combustion that can control pollutant emissions below practically permitted limits without a decrease in combustion intensity. In a previous report⁽¹⁾ we examined a high intensity combustion method which combines a strongly swirling air flow with twin-fluid fuel injection of a wide spray angle, and found that a staged combustion method has a potential of controlling NO_x emissions even under high intensity conditions.

However, in order to obtain high intensity combustion while applying a conventional staged combustion method, in which secondary air is introduced from the side wall of the combustion chamber, many injection holes for secondary air are necessary to promote the mixing of primary combustion gas and secondary air. Moreover, when supplying fuel along the center axis of the combustor and air around the fuel spray in the primary zone, unburnt gas concentrations along the center axis may reach high levels, and if sufficient secondary air is not effectively supplied to the center axis, the combustion flame will elongate downstream.

From these standpoints, we examined the influences of combustion intensity and air/fuel ratio on

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Fig. 1 Schematic of experimental combustor

NO_x emission characteristics; especially fuel NO_x characteristics in nonstaged high intensity combustion. We then studied the effects of primary air ratio and a secondary air injection point on reduction of NO_x emission in a high intensity staged combustion method where the secondary air is injected radially from a multiholed tube inserted from the rear side on the center axis of the combustion chamber.

2. Experimental Apparatus and Techniques

A schematic of the cylindrical combustor is shown in Fig. 1. Strongly swirling air is introduced into the combustion chamber. A fine fuel spray of hollow-cone type with a wide spray angle ($2\theta=155\sim 170$ deg.), formed from a newly-designed twin-fluid atomizer, collides and mixes with the air and burns with a short flame. Because of the formation of a large recirculation zone, a stationary flame is held near the atomizer through a wide range of combustion conditions.

Platinum streamers, Pt-Pt.Rh 13 % thermo-couples, Langmuir ion-probes and water-cooled sampling probes are used, respectively, for local measurements of gas flows, gas temperatures, ion current intensities and gas compositions; these probes are inserted from the measuring ports on the side wall of the combustion chamber and traverse radially within the horizontal crosssection. The exhaust gas is cooled, to stop chemical reactions, using water-cooled tubes in a mixing chamber which is mounted directly at the exit of the combustion chamber. The cooled gas is then sampled by a water-cooled sampling probe and is analyzed by a chemi-luminescence NO_x meter, NDIR type CO/HC analyzer and zirconium O₂ meter.

Fuels used are kerosene with added pyridine of 0~1.69 weight % (fuel N content of 0~0.3 weight %). A little pyridine has no effect on combustion states, and NO_x generated from the combustion of kerosene only can be considered as thermal NO_x.

Fig. 2 Effects of fuel N contents on NO_x emissions

Therefore, NO_x quantities which are calculated by subtracting NO_x contents for kerosene from the values for pyridine-containing fuel can be considered the fuel NO_x concentrations. Experimental conditions are as follows; fuel flow rate $W_f=0.75\sim 4.5$ g/s, combustion air flow rate $W_{ac}=8.4\sim 80$ g/s, atomizing air flow rate $W_{aa}=4$ g/s, combustor heat release rate $q_c=3.6\sim 22$ MW/m³, Sauter's mean diameters of spray $\bar{d}_s=23\sim 35$ μm and swirl number $\cong 1.3$.

At an air ratio λ above 1.05, blue flame combustion can be completed within the combustion chamber.

3. Combustion Characteristics of Non-staged Combustion

Figure 2 shows the effects of NO_x emissions on the air ratio λ and pyridine content. For all experimental conditions, the NO_x emission increases with increasing nitrogen content, showing nearly a proportional change with N content at high air ratios but smaller changes at low air ratios.

Figure 3 illustrates the changes in NO_x emissions

generated from combustions of kerosene only and kerosene mixed with 0.2 wt.% pyridine, calculated fuel NOx emissions and the conversion ratios of fuel N against the combustor heat release rate q_c . The NOx emission for kerosene with pyridine decreases with decreasing combustion intensity due to a decrease in thermal NOx, but the fuel NOx level shows little change. However, when q_c decreases below 6 MW/m^3 , the fuel NOx also decreases because of inadequate mixing of the fuel and air due to the decrease in the air velocity.

Figure 4 shows the changes in NOx emissions, NOx conversion ratios of fuel N and O₂ concentrations with varying air ratios λ under relatively high intensity conditions. The NOx emission from kerosene with pyridine becomes a maximum of about 360 ppm in this case and the fuel NOx level is about 2/3 of the total level. Under fuel-lean conditions, the thermal NOx emission decreases with increasing λ but the NOx conversion ratio increases gradually and much

Fig. 3 Effects of combustion intensities on NOx emission characteristics

Fig. 4 Changes in NOx emission versus air ratios

of the nitrogen in the fuel is converted to NOx. For $\lambda < 1$, the NOx emission decreases significantly with decreasing λ due to the reduction of the local O₂ concentration and temperature.

These experimental results for a high intensity condition such as is obtained by the rapid mixing of a fine fuel spray with air, show that NOx emission attains a high level under fuel-lean conditions. However under fuel-rich conditions, NOx emission decreases significantly with decreasing air ratio. Consequently, it will be expected that applying the staged combustion technique to this method should be effective for realizing low NOx combustion even under high intensity conditions.

4. Reduction of NOx Emission by Staged Combustion

According to the conventional staged combustion method, primary combustion is carried out under fuel-rich conditions, and then perfect combustion is accomplished by injecting secondary air to a downstream position of the combustor. However, in order to apply this technique to high intensity combustion, a specially designed combustion system is required to obtain rapid primary combustion by mixing a fine fuel spray with primary air, and to complete secondary combustion with a short flame by promoting the mixing of secondary air with the unburnt gases of primary combustion.

Therefore, we adopted a new combustion method as shown in Fig. 5, to examine typical staged combustion effects under high intensity conditions. The primary combustion method is the same as in the non-staged combustion mentioned above; namely, rapid fuel-rich combustion is provided by producing a fine fuel spray with a wide spray angle and by supplying strongly swirling air. However, with this structure, burnt gases from the primary combustion flow centripetally to the center axis downstream of the

Fig. 5 Schematic of staged combustion method with high combustion intensity

Fig. 6 Recirculation zone and ion current intensity distributions in the combustion chamber

recirculation zone and are expelled out, so the radial injection of secondary air from the center axis near the exit should be more effective than injection from the side wall in promoting the mixing of unburnt gases with air. Consequently, in this study we adopted the method of injecting secondary air radially from a tube with 8 holes of 7 mm diameter which is inserted from the rear side of the combustion chamber.

Figure 6 shows the changes in recirculation zones and ion current intensity distributions for various primary air ratios λ_1 , which is defined as the primary and atomizing air flow rate versus stoichiometric air flow rate, while keeping the overall air ratio λ constant. The distance Z_2 from the fuel nozzle tip to the secondary air injection point is 200 mm. The solid lines in the figures show the boundary of counter-flow zones and the wave-shaped lines indicate the radial distributions of ion current intensity.

In the combustion by primary air only, Fig. 6(a), recirculation zones are formed near the center axis and at the circumferential corner of the combustor. An active chemical reaction with accompanying vivid ion formation occurs around the central recirculation zone with a blue flame, and finishes 150 mm downstream from the nozzle. The burnt gas temperature ranges from 1700 to 1800 K.

In Fig. 6(b) with secondary air ($\lambda_1=0.8$), the extent of the central recirculation zone decreases and the active primary combustion zone is closer to the center axis. Active reaction with ion formation cannot be observed between the point 150 mm downstream from the nozzle and the secondary air injection point. Downstream of the secondary air supply point, the primary combustion gas is mixed rapidly with secondary air and a secondary combustion zone is formed with accompanying ion production. However the whole reaction is almost completed within the combustion chamber and a high intensity combustion with

two separated combustion zones is obtained. Any changes in the secondary air flow rate with fixed λ_1 do not cause remarkable differences in the ion current distributions in the primary combustion zone, so secondary air injection must not have an obvious influence on primary combustion.

Figure 6(c) illustrates the case of a low primary air supply ($\lambda_1=0.6$). Comparing the ion current intensity with that of Fig. 6(b), the primary combustion zone is shorter and the reaction weaker, but the secondary zone is expanded slightly upstream from the secondary air injection point and a more active reaction is obtained in this region. The temperature just upstream from the secondary zone is about 1400 K.

Figure 7 shows the local NO_x concentrations for kerosene with pyridine corresponding to fuel N=0.2 wt.%, under the same conditions as in Fig. 6. In the case of supplying primary air only, Fig. 7(a), the NO_x concentration increases rapidly within the active ion formation region but changes only slightly in the last part of combustion. Considering that the NO_x concentration by kerosene only is lower than that for kerosene with pyridine, this increase of NO_x in the flame is presumed to be due to fuel NO_x formation. In the case of supplying secondary air, Fig. 7(b), the NO_x level of the primary combustion gas is lower than in the case of kerosene only and increases gradually along the gas flow. Within the secondary combustion zone the NO_x concentration shows a steep distribution along the secondary air flow, but the NO_x level at the combustor exit shows almost the same value as just upstream from the secondary combustion zone. In Fig. 7(c), by supplying less secondary air than in Fig. 7(b), the NO_x level increases slowly in the primary combustion zone but significantly in the secondary combustion zone, and the total NO_x level at the exit is higher than in Fig. 7(b).

Fig. 7 Local distributions of NOx concentration in the combustion chamber: Fuel N=0.2 %

Under these experimental conditions, much of the NOx formed can be said to be fuel NOx. Many fundamental investigations⁽⁶⁾⁽⁷⁾ of the fuel NOx formation mechanism have shown that intermediate materials, i.e. NH_2 , HCN , etc., produced by the decomposition of N compounds in fuel are converted to N_2 under fuel-rich conditions and to NOx under fuel-lean conditions. Nonstaged combustion, in Fig. 7(a), provides a high NOx concentration because almost all the N components in the fuel are converted to NOx within the O_2 -rich flame due to a rapid mixing of the fuel with excess air and thermal NOx is also actively formed. In the staged combustion shown in Fig. 7(b), the NOx concentration increases gradually in the primary combustion zone, and the increase of NOx by the secondary air supply is small before and after the secondary zone. These results show that most N-containing intermediate products are converted to N_2 and NOx and there is little intermediate product to be converted to NOx in the rapid secondary combustion with excess air. On the other hand, for the low primary air combustion shown in Fig. 7(c), since much of the N-containing intermediate product exists without conversion in the primary combustion gas, and is rapidly converted to NOx in the secondary combustion zone, a high NOx concentration appears near the exit where secondary combustion is completed.

An influence of primary air ratio λ_1 and overall air ratio λ on NOx emissions is shown in Fig. 8. NOx concentration is corrected to a 4% O_2 value in order to eliminate the dilution effects with excess air. It can be seen that the NOx emission level is almost determined by λ_1 only, and is independent of λ , which shows that the NOx level depends on the conditions of primary not secondary combustion. Under these experimental conditions, CO and HC concentrations have values below 60 ppm and 10 ppm, respectively.

Figure 9 illustrates the reduction effects of NOx

Fig. 8 Effects of overall air ratios on NOx emissions

Fig. 9 Staged combustion effects under a high intensity condition

Fig. 10 Staged combustion effects under a low intensity condition

emissions versus primary air ratio λ_1 and secondary air injection distance Z_2 under relatively high intensity conditions ($q_c \approx 20 \text{ MW/m}^3$). As λ_1 decreases gradually from 1.1, the NOx emission level for kerosene with pyridine increases then decreases, when secondary air is injected upstream. This shows that primary combustion becomes active when secondary air is supplied into the primary zone because of insufficient separation of the primary and secondary zones. Further decrease of λ_1 leads to a reduction in NOx, and this tendency is more remarkable as Z_2 is increased, because N-containing intermediate products are converted gradually into NOx and N_2 in the deoxidative primary combustion gas, and the converted quantity in the secondary zone decreases with increasing secondary air injection distance Z_2 as shown in Fig. 7(b). With a further decrease of λ_1 to near the burning limit ($\lambda_1 \approx 0.55$), the intermediate products react more weakly in the primary combustion gas and are converted to NOx in the secondary combustion zone, so the influence of Z_2 on the difference in NOx levels decreases, and the increase in NOx level with decreasing λ_1 becomes more remarkable as Z_2 increases.

Figure 10 shows the staged combustion effects at a relatively low combustion intensity ($q_c \approx 5 \text{ MW/m}^3$) while decreasing the fuel flow rate. NOx reducing effects show a tendency similar to that of high combustion intensity, but the multiplication effect of staged combustion and the lowering of combustion intensity provide lower values than those observed under high combustion intensity conditions. λ_1 at which NOx levels are minimized becomes higher and a decreased influence of Z_2 on NOx emission is observed owing to short-flame combustion. The concentrations of CO and HC are about 0.1% and less than 10

ppm, respectively.

5. Discussions

A relatively high combustion intensity can be obtained by colliding a fine fuel spray with a strongly swirling air flow because of rapid mixing and combustion. However, in high intensity combustion with excess air using N-containing fuels, NOx emission of high concentration is simultaneously obtained because sufficient oxygen is uniformly distributed through the flame and much of the N compound in the fuel is converted to NOx. On the contrary, in the case where the air ratio is below unity, NOx emission levels decrease significantly as shown in Fig. 4, so the staged combustion can be regarded as the most effective method for NOx reduction even in a high intensity combustion state.

Under the conditions of high intensity staged combustion, when secondary air is injected upstream and supplied to the primary zone, NOx reduction becomes difficult, but air injection downstream from the primary zone is more effective, as shown in Fig. 9. Therefore, in order to apply a staged combustion technique to high intensity spray combustion, primary combustion by rapid mixing of fine fuel spray with air should be effectively promoted, the secondary combustion zone separated from the primary zone, the primary combustion gas kept under a high temperature deoxidization condition for a long time, and sufficient mixing of the primary combustion gas with secondary air promoted. However, it will be noted that the injection of secondary air near the exit may cause flame elongation out of the combustion chamber and an increase in the emission levels of unburnt gases such as CO and HC, or soot emission due to a decrease in the combustion temperature.

Moreover, by reducing the combustion intensity while keeping good spray characteristics and a constant swirl degree of primary air, NOx can be effectively controlled even under relatively high combustion intensity conditions by the multiplication effect of intensity reduction and staged combustion.

This paper has described the experimental results of typical NOx reduction effects using a high intensity staged combustion method, however, in order to realize a more convenient and practical low NOx combustion of high combustion intensity, it is desirable that the similar effect of staged combustion is obtained by introducing both primary and secondary air from the burner side.

6. Conclusions

From the experimental results of NOx formation for staged combustion in a swirl combustor using N-

containing fuels, the following conclusions were obtained:

(1) The staged combustion which combines a fine fuel spray with strongly swirling air can reduce NO_x emissions even for the conditions of high intensity combustion.

(2) By introducing secondary air downstream, at the position where primary combustion is almost finished, the NO_x reduction effect is more significant.

(3) The most effective primary air ratio for NO_x reduction has a tendency to increase with decreasing combustion intensity.

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References

- (1) Hirai, T., Nagai, N., Koseki, H., Kato, K. and Takado, J., *Trans. Jpn. Soc. Mech. Eng.*, (in Japanese), Vol.51, No.463, (1985-3), p.1077.
- (2) Matsuda, Y., Suzuki, K., Nakamura, Y. and Hamada, T., *Kawasaki Heavy Ind. Techn. Review*, (in Japanese), No.72, (1979-10), p.56.
- (3) Sadakata, M., Nawada, M. and Kunii, D., *J. Chem. Eng. Jpn.*, (in Japanese), Vol.5, No.2, (1979), p. 111.
- (4) Sekiguchi, Y., Okigami, N., Shimotani, H. and Sakai, S., *Hitachi Zosen Techn. Review*, (in Japanese), Vol.42, No.3, (1981-9), p.1.
- (5) Kato, K., Shiraha, M., Kurata, C. and Fujii, K., *Kawasaki Heavy Ind. Techn. Review*, (in Japanese), No.80, (1982-10), p.8.
- (6) Fenimore, C. P., *Combust. Flame*, Vol.19, No.2, (1972-10), p.289.
- (7) Foster, E. D. and Keck, J. C., *Combust. Flame*, Vol.38, No.2 (1980-6), p.199.