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The Relationship Between Firing Modes and Nitric Oxide Emission in Highly Preheated Air Combustion

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The influence of combustion air at temperatures on nitric oxide emission was studied. The nitric oxide emission generally increases with a rise in the temperature of the combustion air. However, if combustion products for dilution of fuel or combustion air are used before the combustion reaction, then the nitric oxide emission can be reduced even when highly preheated air for combustion air is used. Combustion in low oxygen concentrations flattens the firing mode, resulting in a uniform reaction, and, thus, low nitric oxide emission can be achieved.

Key Words : Highly Preheated Air Combustion, Low Nitric Oxide Emission, Mixing Process, Dilution

Nomenclature

I_E : Spatial-average value of emission intensity in an instantaneous image.

$\bar{I}_E$: Time-averaged value of I_E

$i'_{E,n}$: Time-averaged standard deviation of emission intensity of a n-th pixel

$\bar{i}'_E$: Spatial-average value of $i'_{E,n}$

$I_{431.2}$: Emission intensity of the 431.2 nm band

$I_{516.5}$: Emission intensity of the 516.5 nm band

X : Horizontal axis (mm)

Y : Vertical axis (mm)

1. Introduction

Recently, exhaust emission regulations has become more stringent, though energy consumption has been gradually increasing. Within the last several years, great progress has been made to reduce nitric oxides from combustion systems. Techniques for reducing nitric oxide emission should not only reduce nitric oxide emission but also maintain fuel efficiency and heat-transfer requirements. Therefore, Wünnigand (1997) has studied the development of efficient combustion systems which also emit little pollution.

In recent years, Suzukawa et al. (1997) have developed a new technology of highly preheated air combustion and their research has already reached the stage of industrial application.

When highly preheated air above the fuel auto-ignition temperature is used, conventional burner technology such as a flame stabilizer, is no longer needed, because combustion takes place anyway as fuel mixes with preheated air. Preheating combustion air by regeneration is an effective method of saving energy, but nitric oxide emission generally increases with the rise in the temperature of the combustion air. Therefore, many researchers have worked to lower the maximum flame temperature without creating local regions of high temperature in the combustion chamber. Tomeczek, Goral, and Gradon (1995) showed that a diffusion-type burner produced extremely low NOx emissions when furnace gases are intensively entrained into the fuel jet before the flame reaches its maximum temperature.

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Nakamura et al. (1996) studied mixing optimization by applying various firing modes and gas injector designs for a glass-melting furnace. Hasegawa et al. (1992, 1997) produced low nitric oxide combustion in industrial furnaces by using highly preheated air (between 800 and 1200℃ generated by a high-frequency switching heat regeneration system), a fuel-staged combustion, and an extremely high inlet air momentum.

Katsuki et al. (1997, 1990) have shown large changes in the amount of nitric oxide emission with various mixing processes in a combustion system that uses highly preheated air between 1100~1400 K. They found that nitric oxide emission was governed by the maximum temperature and the fluctuating RMS value of the combustor. However, it is difficult to interpret their results with current knowledge about flame structures, chemical kinetics of nitric oxide formation, and destruction mechanisms. Therefore, on not only the conditions and limitations where the above-mentioned combustion can be realized but also the characteristics of an unexplored combustion regime, must be carefully observed.

The purpose of this study is to research the differences in the firing modes of highly preheated air (between 1100-1400K) with various mixtures of air and fuel. The effects of the mixing process between the air and fuel on nitric oxide emission characteristics are also studied.

2. Experimental Apparatus and Methods

The equipment that generates highly preheated air operates in a quasi-steady manner at a high temperature, using a ceramic heat accumulator. Figure 1 shows an apparatus that generates highly preheated air. It consists of two sets of main burners, a pilot burner, and a ceramic heat accumulator. There is another ceramic heat accumulator in front of an escape-duct which is located in the middle of the burner duct. By using either a four-way valve or an exhaust valve, either of the two sets can be operated.

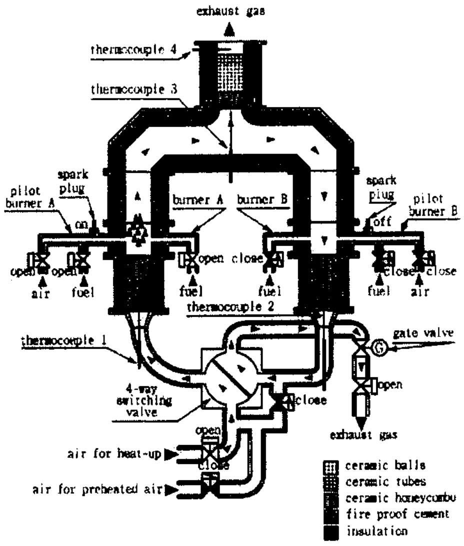


Fig. 1 Generator of highly preheated air

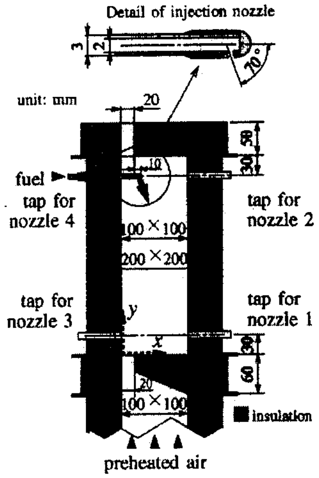


Fig. 2 Combustion chamber

Figure 2 shows the combustion chamber used in this study. The preheated air is supplied through a 100 mm × 100 mm duct. The inlet of the 300 mm-long combustion chamber contracts to a 20 mm × 100 mm cross-section and expands again. Thus, a recirculating flow forms in the chamber. The walls of the chamber are covered by ceramic fiber boards for insulation, and one of the side walls can be replaced with a quartz window to observe the flame. The fuel, city gas 13A, is injected through one of four fuel nozzles indicated in Fig. 2. A fuel nozzle 1.5 mm in diameter is fixed at 10 mm away from the inside wall of the heat insulator for nozzle Nos. 1-2, and 30 mm away for Nos. 3-4. The direction of the fuel injection is set at 70 degrees above to the horizontal axis for fuel nozzles No. 1 and No. 3, and 70 degrees below the horizontal axis for No. 2 and No. 4. The dimensions of the fuel nozzle exits are 2 mm × 1 mm. The fuel injection rate was kept constant at 0.06 L_N/s; the air feed rate was varied between 1.5 and 4.0 L_N/s at the standard condition; and the temperature was varied between 1070 K and 1420 K. Under these conditions, the global excess air ratio varied between 2.27-6.25.

A water-cooled sampling probe with a 0.5 mm suction hole was used to sample the burned gases in the exhaust duct 20 mm downstream from the chamber. The nitric oxide concentration was measured by a chemilluminescence analyzer. Carbon dioxide, instead of fuel, was also injected to simulate the mixing process of fuel with air or burned gases under noncombustible conditions. However, the air was preheated to levels found in combustible conditions. The carbon dioxide concentration was measured with a gas chromatography. Global flame emission distribution was measured with a high speed CCD camera. The emission intensity and the distribution of the 431.2 nm band luminescence (bandwidth = 1.0 nm) were measured to evaluate the emission region in the combustor and to compare the reaction intensity of flames (Dryer and Crosley (1985), Hanson (1986)).

The time resolution was 1/1125 of a second. Spatial resolution was set by the array detector to be 256 × 256. An image intensifier was used to amplify the 431.2 nm band luminescence images. To investigate the reaction uniformity in the combustor, the spectrum was also analyzed by simultaneously measuring the local 431.2 nm band (bandwidth = 1.0nm) and 516.5nm band (bandwidth = 1.6nm) intensities. These two bands are thought to influence the flame color. Because a continuous spectrum of black body radiation was superimposed onto the base of CH and C_2 band signals, the intensity ratio of the two signals has been shown (Tamura et al. (1997), Ito et al. (1986)).

In this study, a newly developed receptor optical system, named Multi-color Integrated Cassegrain Receiving Optics (MICRO), was used to collect light emissions in the 431.2 nm and 516.5 nm bands from the flame (Kauranen et al. (1991), Wakabayashi et al. (1997)). The MICRO system has no chromatic aberration and thus minimizes spherical aberration. The light collection efficiency distribution of the system was evaluated using a ray-tracing method, and the effective volume size was estimated to be 1.6 mm long and 200 μm in diameter. The light emitted through the optical fiber cable was detected by an independent photomultiplier (PM) through dichronic mirrors (DM) and interference filters (IF), as shown in Fig. 3.

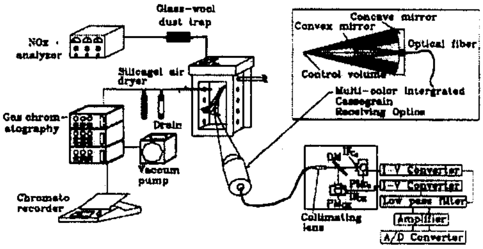


Fig. 3 Detailed diagram of a measuring system

3. Experimental Results and Discussion

Figure 4 shows the variations of nitric oxide emission index versus inlet air temperature. The nitric oxide emission for various conditions were measured, but here only the representative results are presented. The inlet air velocity was calculated to be 7.14 m/s from the air flow rate, the inlet area of the combustion chamber, and the volumetric increase in rising air temperature. The nitric oxide emission index increased with increasing preheated air temperature. Thus, the flame temperature increased as the preheated air temperature increased. However, in spite of the rise in the inlet air temperature, there was little variation in NOx emissions for fuel injection nozzles No. 3 and 4.

Figure 5 shows various levels of nitric oxide emission index versus inlet air velocity. For fuel injection nozzle No. 1, two types of flames were observed, depending on the inlet air velocity. When the velocity was low, a long, bright scarlet,

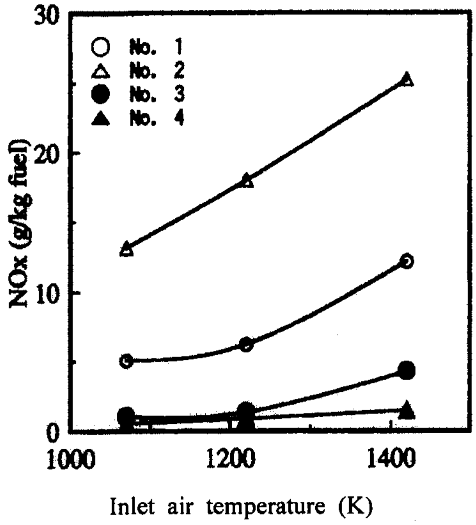


Fig. 4 Influence of inlet air temperature on NOx emission

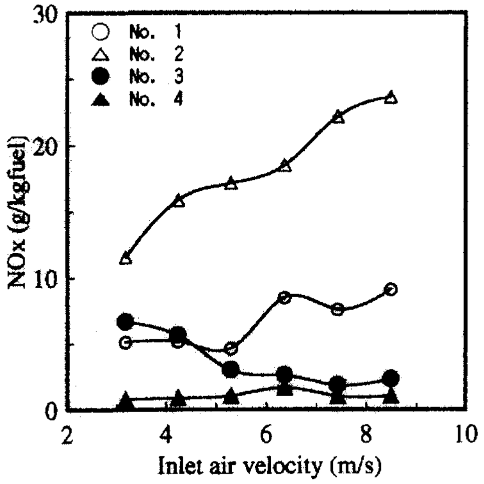


Fig. 5 Influence of inlet air velocity on NOx emission

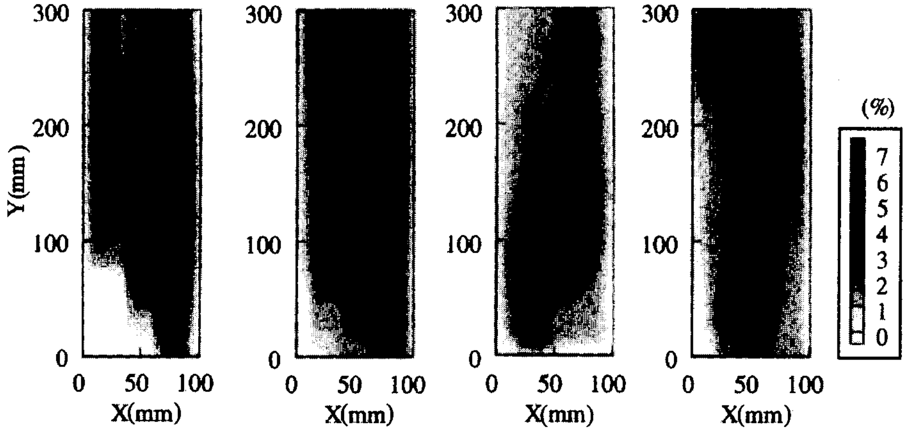
jet-type flame was formed. As the inlet air velocity increased, a block of flames grew at the center of the recirculating flow, emitting strong radiation. Fuel was supplied to the block of flames at the center of the recirculating flows. Therefore, the center area became hotter, and a large amount of thermal nitric oxide was produced. For fuel injection nozzle No. 2, the emission level was extremely high. The fuel was injected against the recirculating flow, and most of the injected fuel was burned near the impingement area. Tanigawa et al. (1998) explained that this phenomenon generated a concentrated local high-temperature region. The nitric oxide emission index of fuel nozzle No. 2 was higher than that for other nozzles, and the variation in the emission index with the change of air inlet velocity also became relatively greater.

For fuel injection nozzle No. 3, a blue flame was formed near the nozzle when the inlet air velocity was low. Also, the mixing of fuel and air was slow, and a long jet flame was formed. With a strong recirculating flow caused by an increase in the inlet air velocity, a very long and stretched reaction zone spread outward. The global emission index of nitric oxide was low, and it decreased with an increase in the air flux. The tendency was quite different from conditions for nozzles No. 1 and 2.

It is thought that the recirculating flow with burned gas may dilute oxygen concentration. Also, the diffusion of fuel by the strong recirculating flow caused by the increasing inlet air velocity, decreased the flame reaction rate. Therefore, the local regions of high temperature in the flame were dissipated, and the nitric oxide emission index was decreased.

For fuel injection nozzle No. 4, when the air velocity was low, the fuel near the impact area of fuel and air were injected because the penetration power of the fuel was weak. Under these conditions, the flame resembled a jet flame. The flame was orange in color, but white color also appeared at the impact area of fuel and air. However, as the fuel injection velocity was increased, the injected fuel entrained the recirculating flow inside. Therefore, the fuel reacted not locally but in the recirculating region containing the burned gas.

Therefore, generation of a local high templntegrated Cassegrain Receiving Optics (MICRO), was used to collect light emissions in the 431.2 nm and 516.5 nm bands from the flame (Kauranen et al. (1991), Wakabayashi et al. (1997)). The MICRO system hahus, the flame temperature decreased and the flame shape was flattened. Therefore, it was found that the emission index of nitric oxide was lower than that at other conditions.



(a) Nozzle 1 (b) Nozzle 2 (c) Nozzle 3 (d) Nozzle 4

Fig. 6 Distributions of carbon dioxide injected instead of fuel.

3.1 The mixing processes for fuel and preheated air

A drastic variation in the nitric oxide emission level was observed when the location of the fuel injection nozzle was changed, even when other experimental parameters, such as the global excess air ratio and the inlet air temperature, were kept constant. To simulate the concentration distribution of the injected fuel, carbon dioxide was used instead of fuel, and a non-combustible mixing field was formed. The heat release due to combustion was not included in the procedure; thus, the actual local concentrations of fuel could not be simulated by this method. However, the mixing facilitated qualitative discussion of the processes in the combustor. Figure 6 shows the concentration distribution of carbon dioxide with various fuel nozzle locations. A large portion of the injected carbon dioxide was caught by the recirculating flow for injection nozzle No. 1. This coincided with the fact that a block of flames was formed at the center of the recirculation zone. Therefore, the local mixture seemed considerably richer than the global excess air ratio, and it was found that most of the nitric oxide was formed in this region. For fuel injection nozzle No. 2, a high concentration of carbon dioxide was observed on the the top and the right side walls of the combustor as well as in the center of the recirculating flow. The mixture seemed worse than in the case of fuel injection nozzle No. 1. A considerable amount of nitric oxide was emitted because the production of nitric oxide depended on the residence time of the burned gas in a high temperature region. For fuel injection nozzle No. 3, a high concentration of carbon dioxide appeared near the entrance of the combustor. Combustion with the incoming preheated air probably occurred in this region, although this high concentration region disappeared as the inlet air velocity was increased. For fuel injection nozzle No. 4, an almost uniform distribution of carbon dioxide was observed, except in the vicinity of the combustor exit. This distribution assured lean combustion throughout the field, and the mixture of the combustion air and the recirculating burned gases might have proceeded to some extent before combustion took place. Therefore, a strong self-exhaust gas recirculation associated with a considerable decrease in oxygen concentration was realized by positioning the fuel nozzle relative to the recirculating flow. It is necessary to produce a mixing condition like this to decrease nitric oxide emission.

3.2 Reaction pattern of flame

The 431.2 nm (CH) band emission distribution was measured with a high speed CCD camera to estimate the reaction pattern of each flame. In this study, flames included soot emission; therefore, a continuous spectrum was superimposed on the CH band emission. Thus, in this study, the 431.2

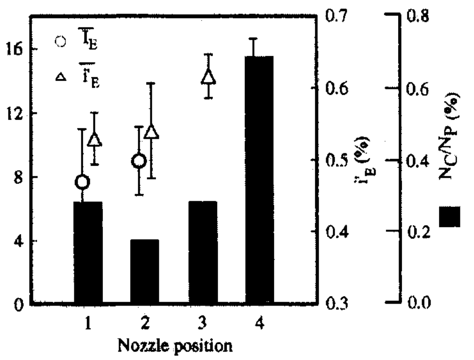


Fig. 7 Emission characteristics of flames with 431.2 nm band detection

nm band emission described not only pure combustion reaction but also soot emission.

However, it is possible to qualitatively discuss about the tendency of the firing mode and its emitting characteristics. Figure 7 shows the distribution of the time averaged 431.2 nm band emission intensity ($\bar{I}_E$) and the spatially averaged RMS of the 431.2 nm band emission intensity ($\bar{i}'_E$), which were calculated from the overall images taken by the CCD camera. The values can be calculated from the equations shown below.

$$\bar{I}_E=\frac{1}{N_F}\cdot\sum_0^{N_F} I_E \qquad (1)$$

$$I_E=\frac{1}{N_P}\cdot\sum_0^{N_P} i_n \qquad (2)$$

where N_F is the number of calculated images, and N_P is the number of pixels that corresponds to the Integrated Cassegrain Receiving Optics (MICRO), was used to collect light emissions in the 431.2 nm and 516.5 nm bands from the flame (Kauranen et al. (1991), Wakabayashi et al. (1997)). The MICRO system haemitting region in the averaged intensity image. The $\bar{i}'_E$ value was calculated by spatially averaging $i'_{E,n}$, which is the time-averaged standard deviation of the n-th pixel.

$$\bar{i}'_E=\frac{1}{N_C}\sum_0^{N_C} i'_{E,n} \qquad (3)$$

$$\bar{i}'_{E,n}=\sqrt{\frac{1}{N_C}\sum_0^{N_F}(i_n-\bar{i}_n)^2} \qquad (4)$$

where Nc is the number of pixels that corresponds to the emitting region in the averaged intensity image. Therefore, $\bar{I}_E$ is related to the intensity of the combustion reaction or heat generation, and $\bar{i}'_E$ indicates the fluctuating characteristics of a reaction. The larger the $\bar{i}'_E$ value, the greater the fluctuation of flames with the passage of time in the combustion chamber.

The N_C/N_P value that is hatched indicates the area ratio of the emitting region to the combustion chamber. Therefore, nozzle No. 4's flame was the most widely dispersed one in the combustion chamber. For fuel injector No. 4, $\bar{I}_E$ was relatively large, but $\bar{i}'_E$ was small. Therefore, it can be imagined that the flame reacts in a wide area and the local reaction is uniform with time. On the other hand, nozzle No. 2 showed a low N_C/N_P ratio, but $\bar{i}'_E$ was larger, compared to nozzles No. 1 and 4. A strong emission with a large fluctuation was concentrated in the limited region. For fuel injection nozzle No. 3, $\bar{I}_E$ was relatively low, in spite of the high value of $\bar{i}'_E$. It is believed that such a flame reacts locally with very weak emission. Nozzle No. 3's flame resembled fog, and it reacted slowly with the recirculating flow in the chamber center. Thus, the combustion characteristics changed dramatically with the positioning of the fuel nozzle. A uniform reaction as in the case of nozzle No. 4 probably resulted from diluting the pure highly preheated air with the recirculating burned gas. Therefore, to form a uniform reaction field, it is necessary to inject the fuel at an appropriate angle toward the recirculating flow to promote air dilution with the burned gas.

If the burned gas is mixed with highly preheated air or fuel before the combustion reaction without forming an ordinary diffusion flame, a relatively low oxygen combustion and a slow uniform reaction will occur. Therefore, nitric oxide emission could be reduced.

If the reactions in the combustor were uniform, the spatial variation of flame colors would be small. To investigate the spatial reaction uniformity and flame color variation, the ratio of the overall intensities of the 431.2 nm band and the 516.5 nm band were measured. The ratio of the 516.5 nm band intensity ($I_{516.5}$) to the 431.2 nm ($I_{431.2}$) band intensity becomes larger as the fuel content in the luminous reaction zone increases.

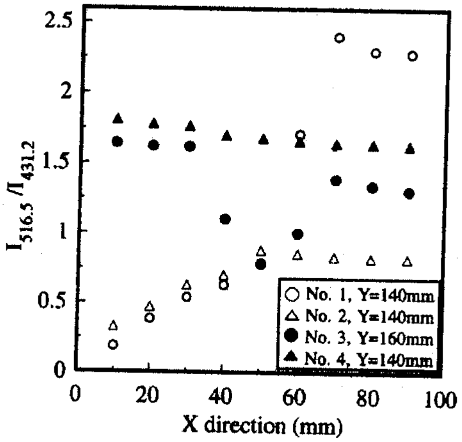


Fig. 8 Distribution of emission intensity ratios of two bands (431.2 nm & 516.5 nm)

The distribution of $I_{516.5}/I_{431.2}$ is shown in Fig. 8. The measured cross-section was near the center of the y-direction. The measured cross -section was at y = 140 mm for nozzle Nos. 1, 2, and 4, and 160 mm for nozzle No. 3. There was little variation in the x-direction for nozzle No. 4. Its values were higher than those for other conditions due to a flattened reaction with a uniform mixing process and a low oxygen concentration in the combustor. This dilution of fresh air or injected fuel delays auto-ignition. On the other hand, for nozzle No. 2, the low ratio values were caused by a concentrated reaction between pure oxygen and pure fuel in the confined region. This counterflow flame resulted in a considerable nitric oxide emission. For nozzle No. 3, a low value region was observed, even though the emission from the flame was very weak. A long, stretched, blue flame in the recirculating region caused the intensity ratio of $I_{516.5}/I_{431.2}$ to be low. For nozzle No. 1, a large gradient was observed, and the maximum value was higher than those at other conditions. This result could be ascribed to a block of flames that was generated in the recirculating region. That is, the fuel might burn at the center of the recirculating region. Therefore, in this study, the intensity ratio $I_{516.5}/I_{431.2}$ can be used as an indicator for judging the reaction uniformity of the combustion reaction regime, high thermal efficiency and low nitric oxide emission.

4. Conclusion

The emission index of nitric oxide, firing modes, and combustion reactions were changed considerably by varying the mixture of fuel and air in a gas diffusion flame that used preheated air at temperatures between 1100-1400K. If highly preheated air hotter than the self-ignition temperature is used as combustion air, a combustion reaction always resulted, even under intensely diluted conditions in which combustion could not occur under ordinary conditions.

In addition, air dilution or fuel dilution with the burned gas resulted in a flattened flame and a uniform reaction in the combustor. It was also effective in reducing nitric oxide emission.

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