# Low $NO_x$ Combustion by a Cyclone-Jet Combustor*

Yoshiaki ONUMA**, Taku YAMAUCHI**
Masayuki MAWATARI**, Masaharu MORIKAWA**
and Susumu NODA**

For achieving a stable premixed combustion, there is a device termed the cyclone combustor, which consists of a cylindrical chamber and fuel nozzles installed tangentially on the sidewall. In this combustor an extremely stable flame can be obtained in the swirl flow, formed along the inner wall of the combustor. The authors utilized this combustor as a flame holder, to burn a high velocity jet flowing axially in the central part, and termed this new combustor a cyclone-jet combustor. In the present study, an excellent flame stability is shown for the cyclone-jet combustor and, by comparing premixed, non-premixed and partially premixed flames, the low $NO_x$ combustion characteristics were experimentally examined for this combustor.

***Key Words***: Burner, Swirl, Pollutant, Gaseous Fuel, Partially Premixed Combustion, Nitrogen Oxide

## 1. Introduction

A device termed the cyclone combustor is available for stable combustion, which consists of a cylindrical chamber and fuel nozzles installed tangentially on the sidewall. In this combustor an extremely stable combustion is possible in the swirl flow, formed along the inner wall of the combustor. In the present study, the combustion of fuel jets of high velocity was attempted by utilizing a cyclone combustor as a flame holder. This new combustor will hereafter be termed a cyclone-jet combustor.

Though the cyclone-jet combustor may be widely used because of its excellent flame-holding performance, in this experiment, by comparing premixed, non-premixed and partially premixed flames, the low $NO_x$ combustion characteristics and the combustion mechanism bringing about these characteristics were examined for the cyclone-jet combustor.

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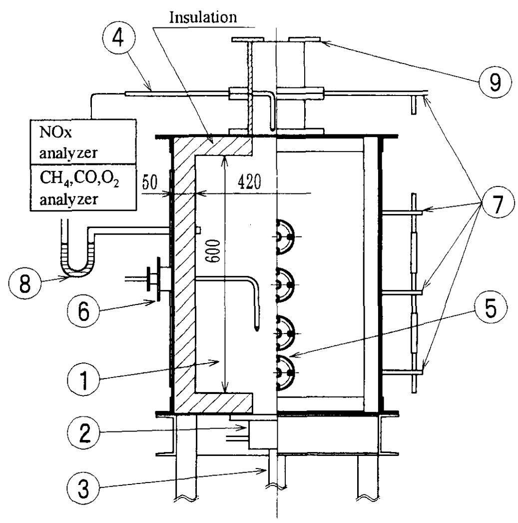
** Department of Mechanical Engineering, Toyohashi University of Technology, Tempaku-cho, Toyohashi 441-8580, Japan. E-mail: onuma@mech.tut.ac.jp

## 2. Experiments

The experimental apparatus, shown in Fig. 1, consists of a combustion chamber ① and a cyclone-jet combustor ②. The combustion chamber is 600 mm in




1. Combustion chamber
2. Cyclone-jet combustor
3. Main-jet nozzle
4. Gas sampling probe
5. Window
6. Probe traverse mechanism
7. Thermocouple
8. Manometer
9. Variable throttle

Fig. 1 Schematic of combustion apparatus

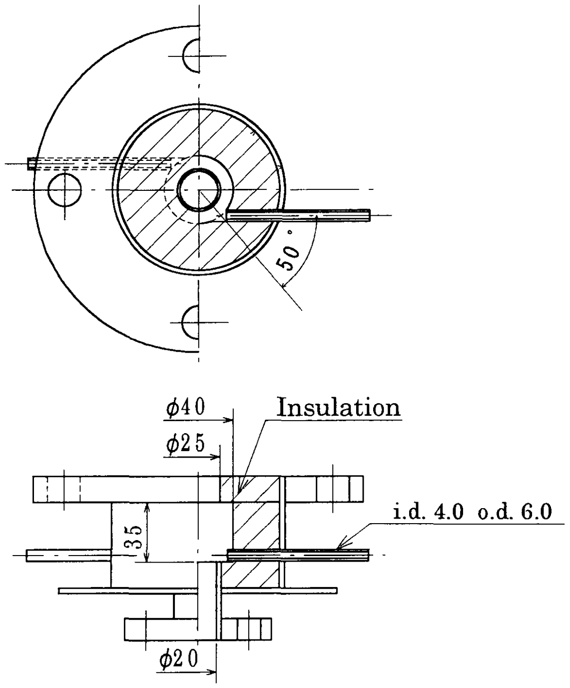



Fig. 2 Cyclone-jet combustor

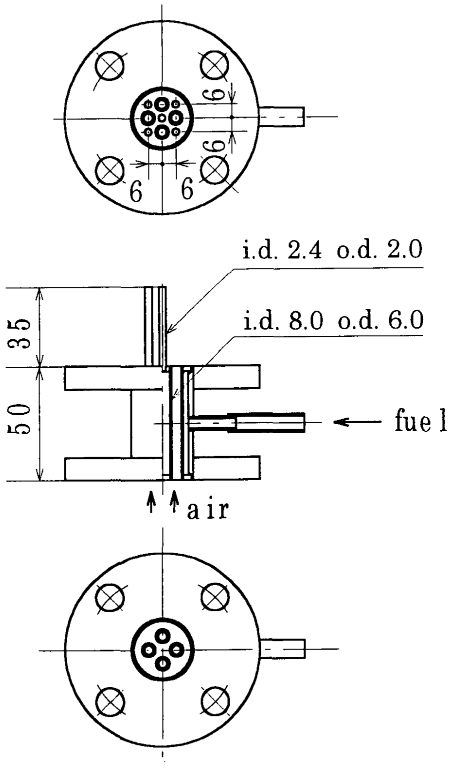



Fig. 3 Main jet nozzle

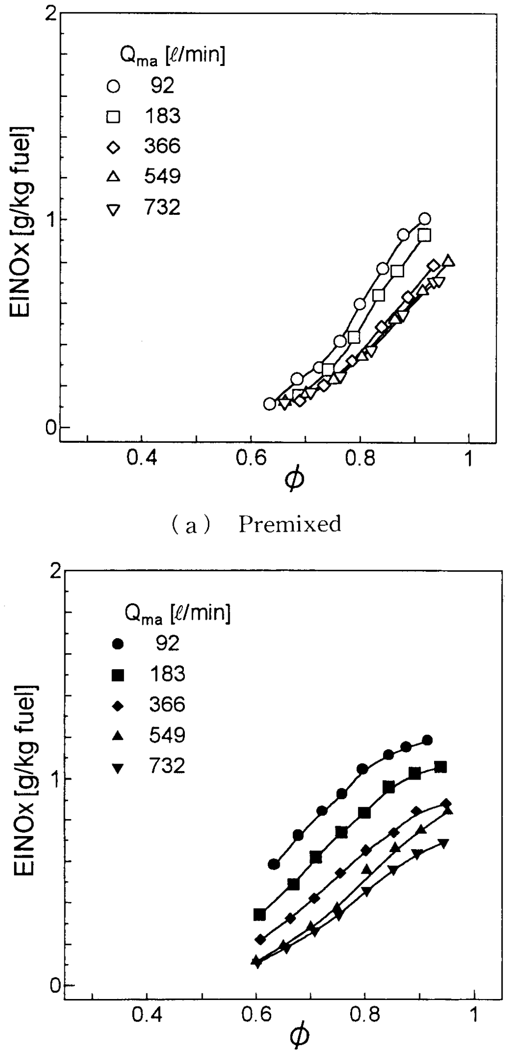
height with a square cross section of 420 mm × 420 mm, and the inner wall is lined with thermal insulation. A cyclone-jet combustor is upwardly installed at the center of the bottom. There is an exhaust hole of 80 mm diameter at the center of the top wall. The cyclone-jet combustor, shown in Fig. 2, is cylindrical, and has two swirl nozzles of 4 mm diameter installed tangentially on the lower part of the side wall and a main jet nozzle at the bottom center. The major part of fuel is supplied through the main nozzle. Premixed gas spouted through the swirl nozzles forms an extremely stable flame circulating along the cylindrical inner wall, and this flame works as a powerful pilot flame for the main jet flame. The cyclone-jet combustor is connected to the combustion chamber by a connecting hole of 25 mm diameter. Figure 3 shows a main jet nozzle, which consists of 5 fuel-jet capillaries of 2 mm inside diameter and 4 air-jet capillaries of 6 mm inside diameter, and performs excellently to bring about rapid mixing of fuel and air. Only the air-jet capillaries were used in the experiment of premixed combustion. Propane was used as the fuel.

Though attention was paid to achieve air-tightness in the construction of the combustion chamber, a small leakage of air occurred due to a slight vacuum during combustion. The experiment was conducted under atmospheric pressure, by controlling a variable throttle at the exhaust hole. The concentrations of $NO_x$, $O_2$, CO and $CH_4$ were measured after sampling the exhaust gas at the center of the exhaust hole. It was confirmed that the gas composition was uniform over the cross section of the exhaust hole. The total equivalence ratio ($\phi$), used later in this report, was calculated using the gas composition determined for the exhaust gases. Temperature was measured amidst the flames by a Pt-Pt/13%Rh thermocouple coated with $Y_2O_3$-BeO. Correction for radiation error was not conducted.

## 3. Experimental Results and Discussion

### 3.1 Premixed combustion and non-premixed combustion

Figure 4 shows the behavior of $NO_x$ emission in the cyclone-jet combustor. Figures 4(a) and (b) indicate the experimental results of premixed and non-premixed combustions, respectively. The ordinate is an emission index of $NO_x$ ($EINO_x$), which is the gram number of $NO_x$ emission per 1 kg of fuel, and the abscissa ($\phi$) is the total equivalence ratio. The parameter ($Q_{ma}$) is the air flow rate in the main jet, and an increase of $Q_{ma}$ brings about the increase of turbulence which promotes mixing. Under the same equivalence ratio, the increase of $Q_{ma}$ also means an increase of fuel flow rate. When $Q_{ma}$ is the maximum, 732 l/min, the air jet velocity is 108 m/s. To form a pilot flame the premixed gas of propane and air was spouted in the flow velocity $U_p$=20 m/s. Its equivalence ratio ($\phi_p$) was 0.55. Since a fuel-lean premixed flame was used as a pilot flame, $NO_x$ emission from the pilot




( a ) Premixed



( b ) Non-premixed

Fig. 4 $NO_x$ emission in premixed and non-premixed combustion

flame was negligible compared to the main jet flame.

Figure 4 ( a ) shows that stable premixed combustion is possible in the fuel-lean state of $\phi \fallingdotseq 0.6$, and it is known that the cyclone-jet combustor has excellent flame stability. Naturally $NO_x$ emission is small in this lean premixed combustion. Although $EINO_x$ decreases with an increase of turbulence caused by an increase of $Q_{ma}$, the decrease is small, and in particular it is very slight in the high turbulence region of $Q_{ma}>366$ l/min. Compared to this behavior of premixed combustion, it is observed in the non-premixed combustion of Fig. 4 ( b ) that the increase of $Q_{ma}$ causes a large reduction of $EINO_x$. Promoting the mixing by increasing $Q_{ma}$, the behavior of $NO_x$ emission from the non-premixed combustion becomes similar to that from the premixed combustion, and both behaviors are nearly the same in the maximum air flow rate of $Q_{ma}=732$ l/min. Though $NO_x$ emission can be considerably reduced by decreasing the equivalence ratio in the premixed flame, this reduction is generally difficult in non-premixed flames. However, the foregoing results indicate that a similar $NO_x$ reduction can also be obtained in non-premixed combustion as well as in premixed combustion, by enhancing turbulent mixing in the cyclone-jet combustor. Only the data of complete combustion, where the CO concentration in exhaust gas is less than 200 ppm, were selected for this report.

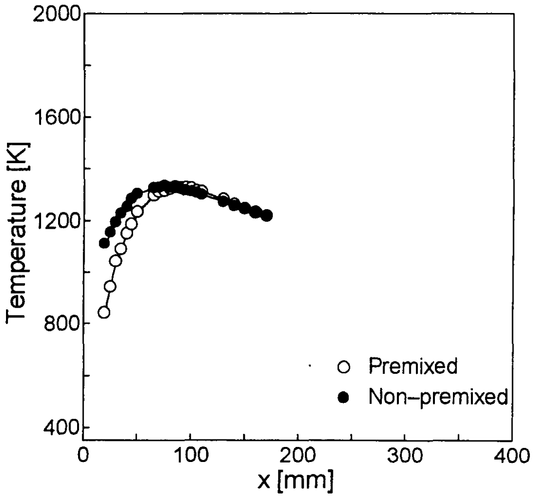
In order to examine the mechanism which causes this $NO_x$ emission behavior, time-averaged temperature was measured amidst the flames by a thermocouple. Figure 5 shows the comparison of axial temperature distributions for premixed and non-premixed flames at $\phi=0.7$. Figures 5 ( a ) - 5 ( c ) indicate the results for $Q_{ma}=183$, 366 and 732 l/min, respectively. The abscissa ($x$) is the distance from the upper surface of the connecting hole. Figure 6 indicates the comparison of radial temperature distributions for the flames shown in Figs. 5 ( a ) and 5 ( c ). Abscissa ($r$) is the distance from the flame axis. Comparing $NO_x$ emission behaviors in Fig. 4 and temperature distributions in Figs. 5 and 6, the following results are observed.

( 1 ) Temperature distributions in the non-premixed flames become similar to those of the premixed flames with an increase of $Q_{ma}$, and subsequently the temperature distributions are almost the same for both kinds of flames at $Q_{ma}=732$ l/min, where the mixing rate is maximum. This tendency of temperature distribution corresponds to the foregoing tendency of $NO_x$ emission shown in Figs. 4 ( a ) and 4 ( b ), where $NO_x$ emission behavior in the non-premixed flames becomes similar to that in the premixed flames with an increase of $Q_{ma}$, and these behaviors finally become almost the same for both kinds of flames.

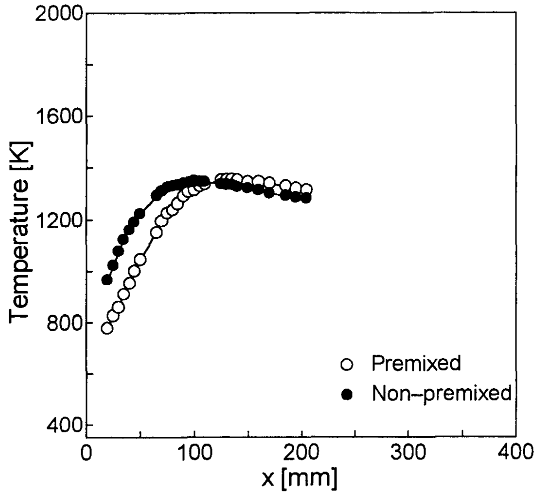
( 2 ) Axial temperature distributions show a steep rise upstream and then a slow descent downstream of the peak. Comparison of temperature distributions for both kinds of flames shows that there is no difference downstream and the difference is observed only in the region upstream of the peak.

( 3 ) Almost all chemical reactions occur in the temperature-rising upstream region in these type of jet flames. This fact was confirmed by measuring the CO concentration within the flames. Therefore, it is conjectured that rapid mixing approaches the structure of the reaction region in non-premixed flames to that in premixed flames, and this phenomenon exerts a large influence on $NO_x$ formation.

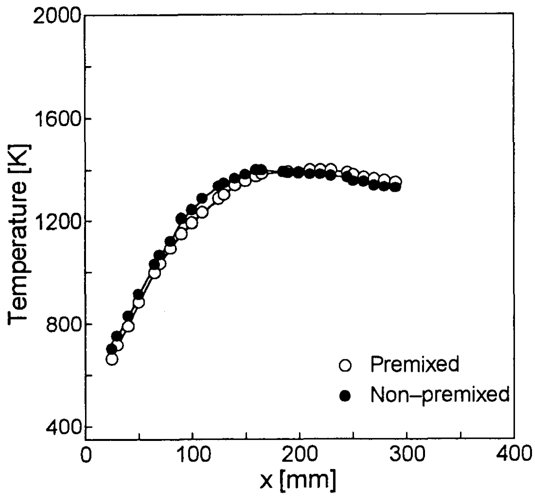
The flame structure in the cyclone-jet combustor is assumed as shown in Fig. 7. The swirl nozzles




( a ) $Q_{ma}$=183 l/min

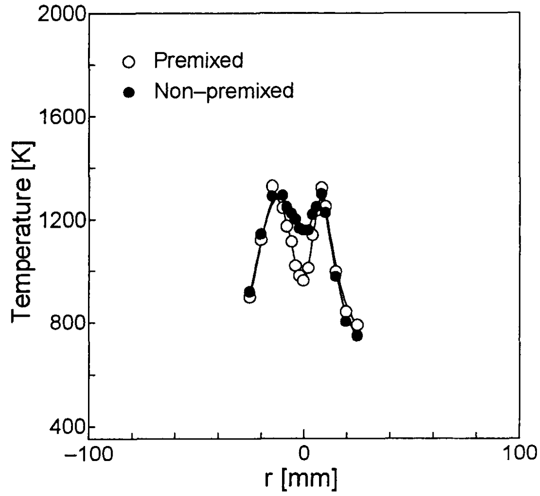



( b ) $Q_{ma}$=366 l/min

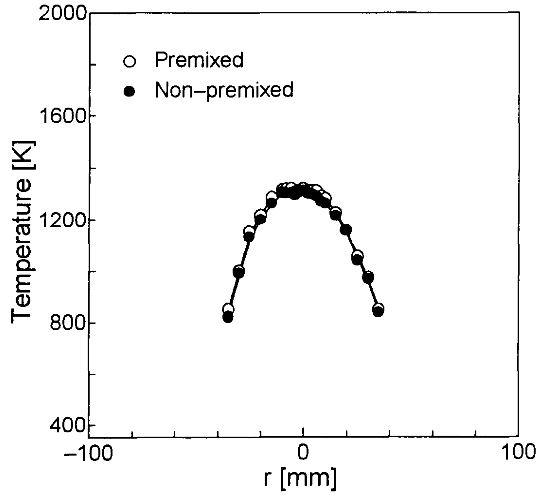



( c ) $Q_{ma}$=732 l/min

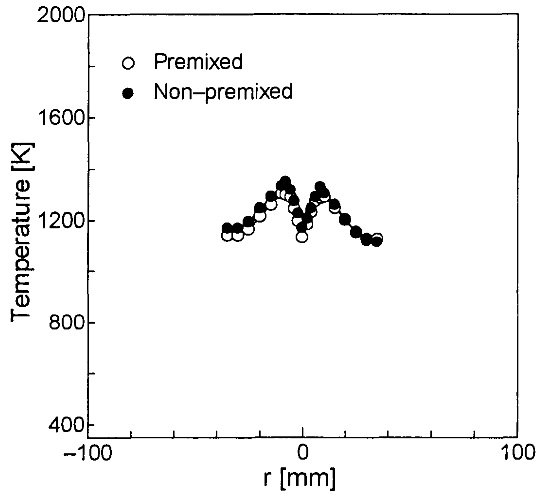
Fig. 5 Comparison of axial temperature distributions for premixed and non-premixed flames




( a ) $Q_{ma}$=183 l/min, $x$=25 mm




( b ) $Q_{ma}$=183 l/min, $x$=80 mm




( c ) $Q_{ma}$=732 l/min, $x$=80 mm

Fig. 6 Comparison of radial temperature distributions for premixed and non-premixed flames

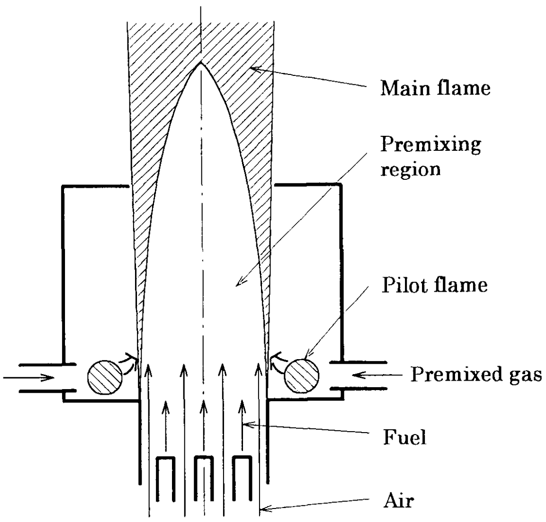



Fig. 7 Combustion mechanism of cyclone-jet combustor

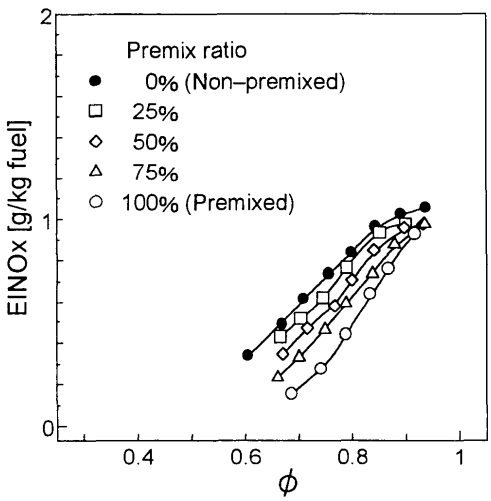



Fig. 8 $NO_x$ emission in partially premixed combustion, $Q_{ma}=183$ l/min, $\phi=0.7$

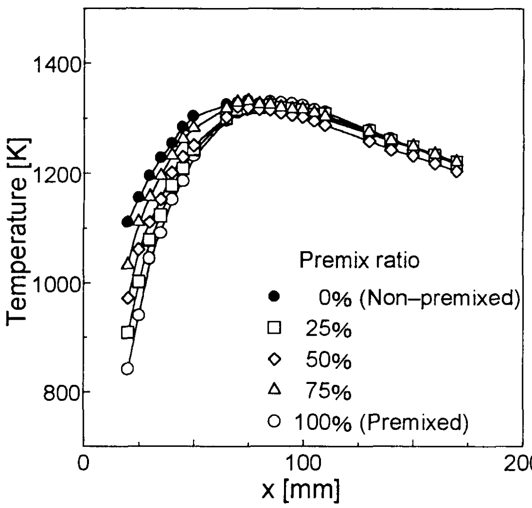



Fig. 9 Comparison of axial temperature distributions for partially premixed flames, $Q_{ma}=183$ l/min, $\phi=0.7$

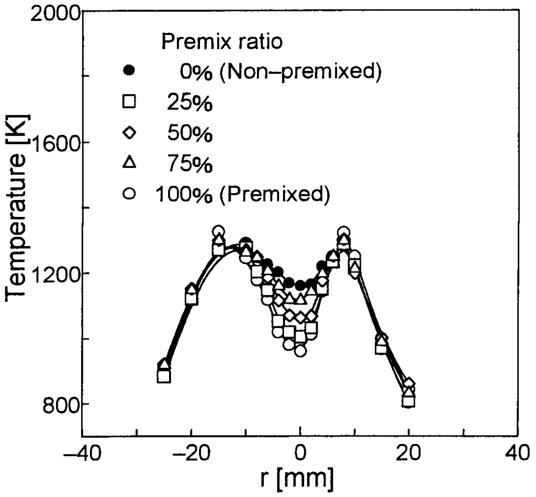
shown in Fig. 2 form a recirculating flame at the bottom of the combustor, and this circular premixed flame supplies flame fragments to the main jet as a pilot flame. The fragments entrained to the peripheral region of the main jet are transferred downstream, and extend the reaction region toward the central part of the main jet. Then, there is a time lag till the fuel spouted from the nozzle burns. Because the nozzle has a structure as shown in Fig. 3, premixing of fuel and air takes place during this time lag. This premixing is promoted by an increase of turbulence. It is conjectured that, due to this premixing, temperature distributions are nearly the same and the $NO_x$ emission behaviors coincide for both kinds of flames, in the case with the largest turbulence, $Q_{ma}=732$ l/min.

### 3.2 Partially premixed combustion

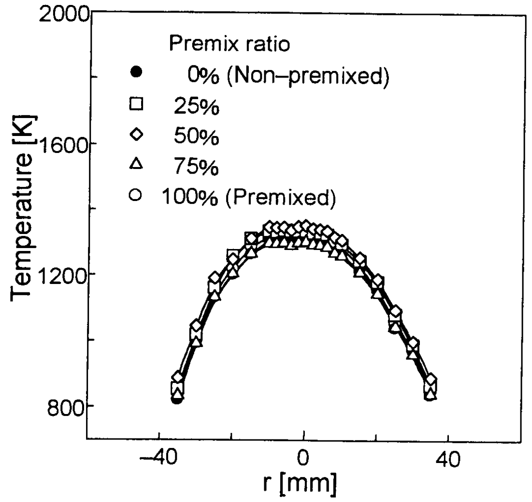
It was assumed in section 3.1 that, even when fuel and air are not premixed at the entrance of the combustor, premixing is possible before ignition in the cyclone-jet combustor, which makes extremely low $NO_x$ combustion possible. If this assumption is true, then partial premixing of fuel and air before spouting ought to reduce $NO_x$ even in low turbulence condition. To confirm this assumption a part of the main jet fuel was premixed with air under constant flow rates of fuel and air, and $NO_x$ concentration in the exhaust gas and temperature distributions within flames were measured for the partially premixed flames. Experiments were carried out on 5 flames in which 0, 25, 50, 75 and 100% of the flow rates of main jet fuels were premixed with air. The 0% and 100% partially premixed flames mean a non-premixed and premixed flame, respectively.

Figure 8 shows the behavior of $NO_x$ emission in partially premixed combustion of $Q_{ma}=183$ l/min. The premix ratio in the figure indicates the ratio of the premixed fuel flow rate to the total one. $NO_x$ emission is largest in non-premixed combustion and least in premixed combustion. It is found in partially premixed combustion that the behavior of $NO_x$ emission approaches that of premixed combustion with an increase of the premix ratio. This result proves the conjecture that the premixing after spouting of fuel and air causes extreme $NO_x$ reduction.

Figures 9 and 10 show temperature distributions for the case of $\phi=0.7$ for the five kinds of flames shown in Fig. 8. It is found in the axial temperature distributions of Fig. 9 that the temperature in the region upstream of the peak decreases and approaches that of the premixed flame, with an increase of the premix ratio. There is little difference in the temperature distributions downstream for the five flames, and the difference is found only upstream.




(a) $x=25$ mm




(b) $x=80$ mm

Fig. 10 Comparison of radial temperature distributions for partially premixed flames, $Q_{ma}=183$ l/min, $\phi=0.7$

In Fig. 10, each temperature distribution shows a saddle shape upstream. There is little difference in the distributions of the outer regions, but the difference is limited only in the reaction zone of the central part. The change of the temperature distributions in Figs. 9 and 10 obtained with an increase of the premix ratio in the partially premixed flames closely resembles the change shown in Figs. 5 and 6 obtained with an increase of mixing rates in non-premixed flames.

## 4. Conclusions

Using a cyclone-jet combustor originated in the present study, the behaviors of $NO_x$ emission were compared experimentally for premixed, non-premixed and partially premixed combustion. The conclusions are as follows.

(1) In the cyclone-jet combustor, turbulent lean premixed combustion is possible in the equivalence ratio of 0.6 due to its excellent stability. $NO_x$ emission is naturally low in such a lean premixed combustion.

(2) $NO_x$ emission in non-premixed combustion can nearly be reduced to that of premixed combustion by an increase of mixing rate.

(3) This behavior of $NO_x$ reduction is assumed to be caused by the phenomenon that spouted fuel is premixed with spouted air during the time lag until ignition. The experiment on partially premixed combustion confirmed this conjecture.

(4) The phenomenon that fuel gas spouted from a nozzle is mixed with surrounding oxidizer until ignition, does not happen only in a special case of the cyclone-jet combustor, but it is often seen in actual combustion fields. The present authors intend to examine this phenomenon in detail.

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