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# Characteristics of Low $NO_x$ Diffusion Combustion with Strong Swirl Flow

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## ABSTRACTS

Though the lean premixed combustion technology is the most effective means to reduce $NO_x$ emission from gas turbine combustors, consideration to prevent the mixture from flash-back or self ignition is necessary in designing a premixed type combustor. Then, the authors have devised a newly designed combustor where fuel and air supplied to the combustor mixes with each other rapidly by a highly turbulent shear flow generated by a strong swirl flow.

To examine the availability of the rapid mixing diffusion combustor fundamental experiments have been conducted using a simplified can-type model combustor. The exhaust emission characteristics show the low $NO_x$ performance and high combustion stability in case of a suitable fuel injection position, but, when fuel injected from an inadequate position, unburned fuel and carbon monoxide are emitted in the exhaust combustion gas. Measurements on the air velocity near the upstream end of the combustor at a cold state indicates that a high speed and turbulent shear flow region exists near the liner wall and the fuel injected into the shear air flow is expected to be rapidly mixed with air. As the result, a premixed-like combustion seems to be realized to prove the exhaust emissions.

## INTRODUCTION

Various ways to reduce $NO_x$ (thermal) emission from a gas turbine are applied to practical combustors and the lean premixed combustion is considered to be the most available and effective technology. However, the fuel/air mixture leads to flash-back or self-ignition at some conditions and is limited for stable combustion. The conventional ways to stabilize the flame need complicated structures and fuel control systems.

Then, the authors have designed a new type combustor, where the fuel injected into a highly turbulent shear flow region mixes with air in a very short duration, so that premixed-like combustion occurs to realize a very low $NO_x$ emission. Moreover, the strong swirl motion also keeps the combustion reaction stable in the upstream region.

Application of strong swirl flow to a combustor has been tried by several researchers. Tanasawa et al. (1) have conducted an experimental study on the combustion characteristics of a diffusion vortex combustor, and Onuma et al. (2) have reported experimental results on the combustion stability and exhaust emissions of a lean premixed vortex combustor. They obtained a stable combustion by the vortex motion in wide operating conditions. Gabler et al. (3) have also reported experimental and simulated results obtained by a simple diffusion combustor model, which is based on almost the same idea as the present study. They obtained a low $NO_x$ emission characteristics and high combustion stability by a rapid fuel/air mixing concept, but their experiments and analytical simulation were not systematically conducted on the influence of fuel injection or air flow condition on the exhaust emissions and stability limit, so that the most suitable conditions of fuel injection and the influence of combustion load on $NO_x$ emission could not be found out.

The authors have expected to examine the applicability and availability of the low $NO_x$ technology based on the rapid fuel/air mixing by swirling air flow to a practical combustor by a series of experiments using a model combustor. This paper describes the experimental results on the flame appearances and exhaust emissions as the function of fuel injection conditions and combustion load.

## STRUCTURE OF THE DIFFUSION COMBUSTOR MODEL AND EXPERIMENTS

The combustor model used in these experiments is indicated in Fig. 1, which has a very simple can structure of 90 mm in inner diameter and 300 mm in length. The downstream end of the combustor is open to the atmosphere and the combustion air is supplied at a room temperature near 300 K. Pure methane (purity 99 %) in place of natural gas is injected from the single port provided on the upstream end plate of the combustor. Since the fuel jet momentum and the injection position are expected to be the factors affecting the combustion characteristics and exhaust emissions, the authors adopted them as the experimental parameters. The fuel injection position can be adjusted to an arbitrary combination of radial position and circumferential angle by using a specially designed combustor end plate. An air introduction port with a rectangular cross section of 6 mm in width and 17 mm in axial height is prepared at an axial position 10 mm apart from the combustor upstream end.

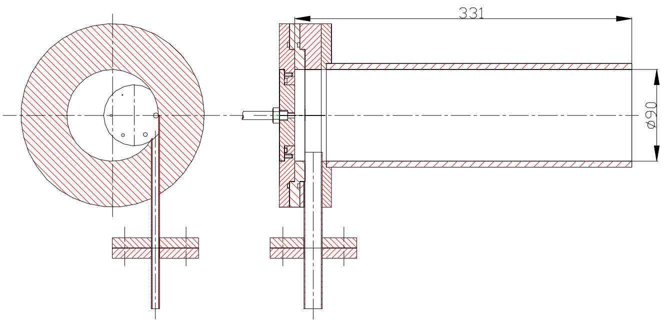

Fig.1 Model combustor for experiments

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The parameters adopted in the experiments are indicated in Table 1. Since the fuel jet momentum depends on the diameter of fuel injection port for a certain fuel flow rate, the fuel port diameter was changed from 3 to 6 mm to examine the effect of fuel jet momentum on the combustion performances. The radial position and circumferential angle of fuel injection port will give remarkable influences on the rate of fuel mixing with air, which affects the flame structure, flame stability and in consequence the exhaust emission.

Table 1 Experimental parameters

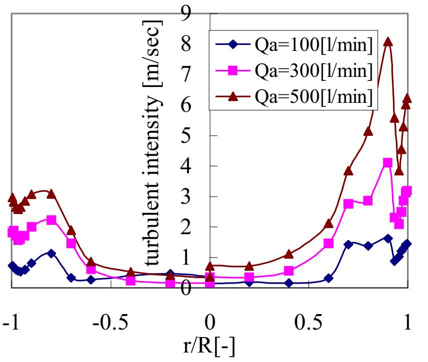
| | |
|---|---|
| Airflow rate $Q_a$ [l/min] | 100,200,300,400,500 |
| Air ratio [-] | 5.00, 2.50,1.67,1.25 |
| Fuel injecting position $r_f/R$[-] | 0,0.67,0.94 |
| Fuel nozzle diameter $D_f$ [mm] | 3,4,6 |

## FLOW CHARACTERISTICS NEAR THE UPSTREAM END

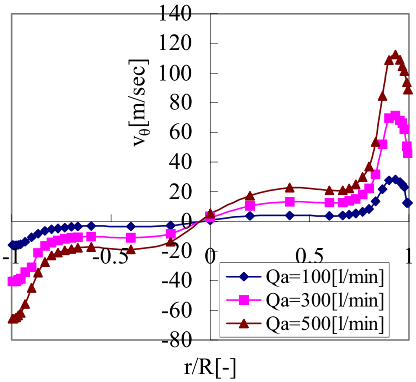
Fuel injected from the injection port provided in the upstream end plate of the combustor is expected to be mixed with a turbulent air flow, which is made by a high-speed air jet introduced tangentially from the rectangular port. Figure 2 indicates the radial distribution of turbulent intensity in (a) and tangential velocity in (b) across the airflow inlet port at the cross section of 8 mm away from the end plate measured by a hot wire anemometer in a cold flow for three different air flow rates. The upstream end of the rectangular port is 10 mm apart from the combustor upstream end plate in the case.

There exists a high tangential velocity field between the 2/3 of the combustor radius and the combustor liner wall, and also it produces a very high turbulence intensity field. On the contrary at the inner region of 2/3 radius circle the tangential velocity is very low and the turbulent intensity is remarkably weak compared with the outside flow region. The difference of airflow rate does not bring about any striking difference of relative distribution of tangential velocity and turbulent intensity. The radial distribution is not symmetric of the central axis and at the opposite side of the air inlet port both the tangential velocity and turbulent intensity are low relative to the opposite side.

From the results of velocity measurements mentioned above, when fuel is injected around the central low velocity and weak turbulence region, fuel will mix slowly with air and premixing will not achieve prior to combustion reaction. On the contrary, in case of fuel injection at the outer side where the velocity is high and the turbulence is intense, the fuel will be quickly mixed with air to form a quasi-premixed combustion.



(a) Radial distribution of turbulence intensity



(b) Radial distribution of tangential velocity

Fig. 2 Air flow characteristics in cold state near the upstream end (z=8mm)

## COMBUSTION CHARACTERISTICS

Various kinds of flame are formed according to airflow rate, air/fuel ratio and fuel injection condition. Flame appearances observed at various conditions are indicated in Fig.3. In this case the combustor liner was exchanged to a transparent quartz cylinder. In case of high flow rate condition, as the position of fuel injection port shifts from the combustor center towards the outside direction, the flame appearance changes from a solid and bright yellow flame to a hollow and dark blue flame when observed from the downstream side. That may be caused by the promotion of fuel-air mixing to change to a premixed flame-like condition according to the shift of fuel injection position. The air flow rate also affects the flame appearances at a constant air/fuel ratio and its increase changes the flame color from bright yellow to dark blue in case of outer side fuel injection. At a rich condition, a vortex flame shape can be clearly observed from the outside.

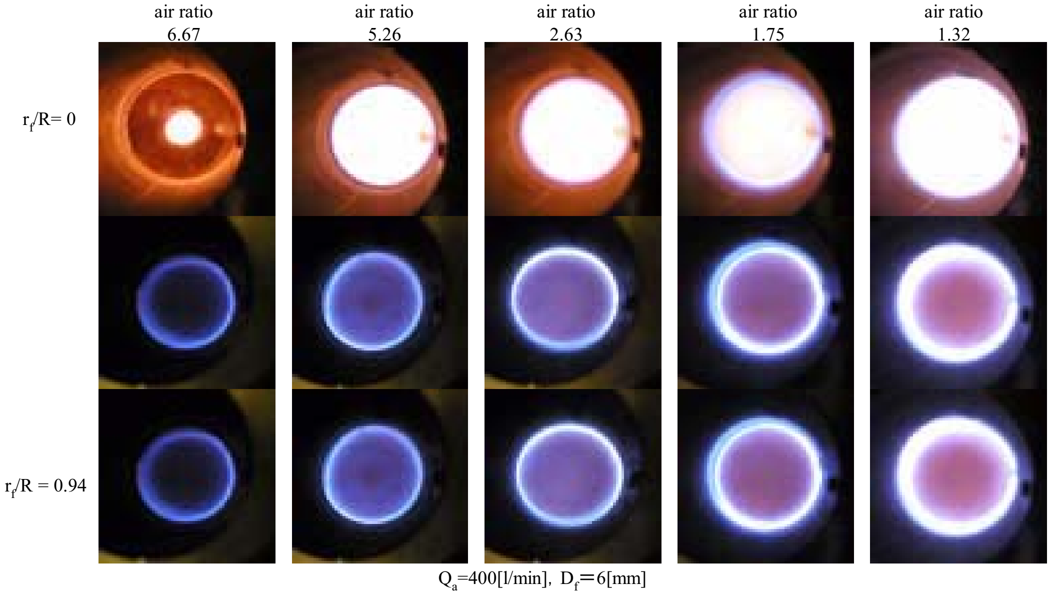


Fig.3 Flame appearances observed from the backside

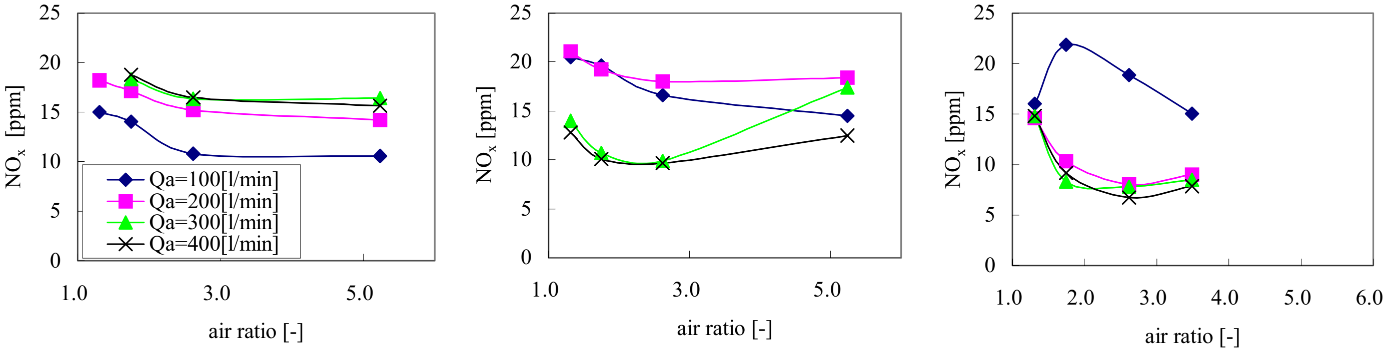
## EXHAUST GAS EMISSIONS FOR VARIOUS CONDITIONS

The exhaust emissions were also measured at the downstream end of the combustor by a gas sampling method for various parametric conditions. To avoid the inflow of atmospheric air and the inaccurate measurements caused by the non-uniformity of gas concentration and velocity at the combustor end cross section, a coaxial cone of 58 mm in diameter was inserted from the downstream and a water- cooled sampling probe was set at the center of annular flow path. The sampled gas was analyzed by $NO_x$, CO, $CO_2$, UHC and $O_2$ analytical equipments. All the values of gas concentration measured by the experiments are converted into the values equivalent for 16 % oxygen.

### Effects of Fuel Injection Position

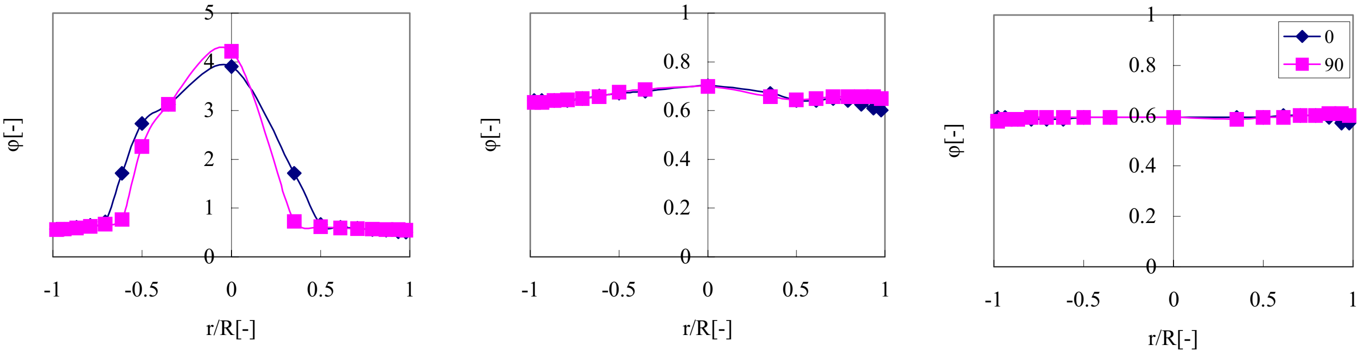
The $NO_x$ emission characteristics were measured at the combustor exit as the function of air ratio, for different air flow rates and different fuel injection positions. In case of fuel injection at the center, $r_f/R=0$, $NO_x$ emission decreases with increase of air ratio as shown in Fig. 4 (a), but the increase of air flow rate brings about increase in $NO_x$ emission. As described above, the air velocity and turbulence intensity in the central region indicate very low level and the fuel injected here is not expected to diffuse rapidly in the air flow. In case of fuel injection at the position of 0.67 in $r_f/R$, $NO_x$ emission decreases strikingly at high flow rate conditions compared with the central injection case over the whole range of mixture ratio as shown in Fig. 4 (b). The velocity gradient increases drastically towards the outer radial position as indicated above, and so the fuel injected here is expected to mix rapidly with air to realize a near-premixed combustion with low $NO_x$ emission. When fuel is injected at the position just near the liner wall, $r_f/R=0.94$, $NO_x$ emission decreases more except the lowest flow rate condition as Fig. 4 (c) indicates. In the lowest flow rate case $NO_x$ emission value changes little regardless of fuel injection position. The low $NO_x$ emission characteristics come out due to the sufficient mixing of fuel and air in a intensely-sheared and turbulent field generated by a steep velocity gradient existing near the liner wall.

To support the reasoning mentioned above about $NO_x$ emission characteristics, experiments on the fuel diffusion in the swirling air were conducted in a cold state. An air jet mixed with small amount of methane whose jet momentum was equivalent to the methane jet was injected from the fuel port and the methane concentration was measured at the downstream by a hydrocarbon analyzer. The air flow rate was fixed at 300 l/min. Figs. 5(a), (b) and (c) indicate the distribution of equivalence ratio converted from measured data of methane concentration, where the air ratio is fixed at 1.67. The distributions shown in the figures are those measured along two right-angled diameters on the cross section 50 mm away from the upstream end. One of the diameters is on the axial cross section passing the exit of air introduction port (indicated by "0" in the figures). When fuel is injected at the center, the diffusion process is hardly promoted in the swirling air flow and a high equivalence ratio region reaching 4 or 5 is observed near the central axis as shown in Fig. 5(a). The experimental results agree with the results of high $NO_x$ emission in the central injection condition. In case of fuel injection at 0.67 of $r_f/R$, fuel diffuses well into the airflow and generates a mixture having a gentle peak of 0.7 in the center as shown in Fig. 5(b). The promotion of fuel and air mixing brings about low $NO_x$ emission as supposed and measured by experiments. In case of fuel injection at 0.94 of $r_f/R$, fuel is almost perfectly mixed with air in a highly turbulent shear flow as shown in Fig. 5(c). As the result of sufficient mixing of fuel and air, premixed combustion can be achieved to generate low $NO_x$ emission as shown in Fig. 4(c).



(a) Case of fuel injection at the center (b) Case of fuel injection at 0.67 of $r_f/R$ (c) Case of fuel injection at 0.94 of $r_f/R$

Fig. 4 NOx emission characteristics as the function of air ratio for various flow rate



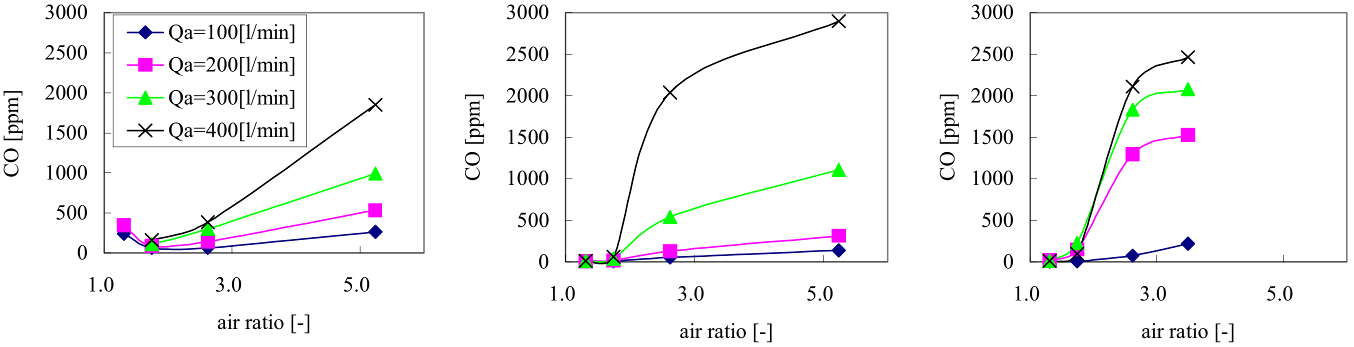
(a) Case of fuel injection at the center (b) Case of fuel injection at 0.67 of $r_f/R$ (c) Case of fuel injection at 0.94 of $r_f/R$

Fig. 5 Radial distributions of equivalence ratio along the two right-angled diameter

The NOx emission reported by Gabler et al. who have conducted experiments similar to this work is about the same order of magnitude, but the emission tendency against the overall equivalence ratio is different. According to their results, NOx emission (equivalent value for a fixed oxygen conc.) increases with the increase of equivalence ratio, though the results obtained in this work indicates the small influence of air ratio (reciprocal of equivalence ratio) on NOx emission regardless of all fuel injection conditions except the case of near- stoichiometric condition. The difference of the NOx tendencies between the two cases may be probably caused by the existense of a recess at the downstream end. The existence of the recess provides a mixing time before chemical reaction and then NOx production rate per fuel is supposed to become about the same value regardless of air ratio.

When fuel is injected near the liner wall, a large amount of unburned ingredients, CO and UHC, is exhausted at the air ratio over 1.67 (0.6 of stoicheiometric ratio) except the condition of fuel injected at the center as shown in Figs. 6 and 7. The more the air flow rate increases, the more the unburned ingredients are exhausted. Especially the increasing tendency is remarkable in the case of fuel injection at 0.94 of $r_f$/R as both Fig. 6 (c) and Fig. 7 (c) indicates. The emission of unburned ingredient exhausted at this fuel jet condition is supposed to be resulted from partial blow-off caused by flame stretch occurring in the intense turbulent shear region near the wall. This explanation should be proved by a detailed measurements of temperature and gas compositions conducted near future. The different tendencies of the central injection condition shown in Fig. 6 (a) and Fig. 7 (a) are probably caused by insufficient mixing of fuel and air in a weak turbulent and low velocity airflow.

Fig. 8 indicates the exhaust emissions as the function of fuel injection position for various mixture ratio conditions. The $NO_x$ emission changes little in its value regardless of fuel injection position at a relatively low air ratio conditions except the case of

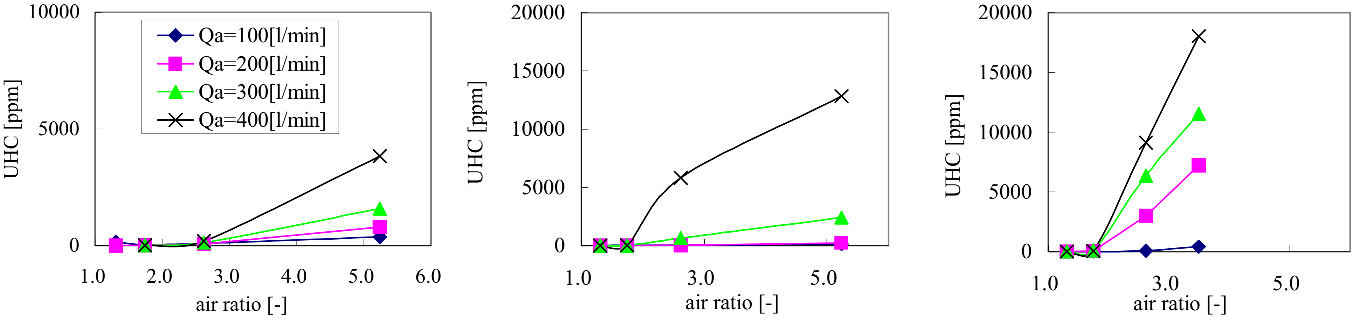


(a) Case of fuel injection at the center

(b) Case of fuel injection at 0.67 of $r_f$/R

(c) Case of fuel injection at 0.94 of $r_f$/R

Fig. 6 CO emission characteristics as the function of air ratio for various flow rate

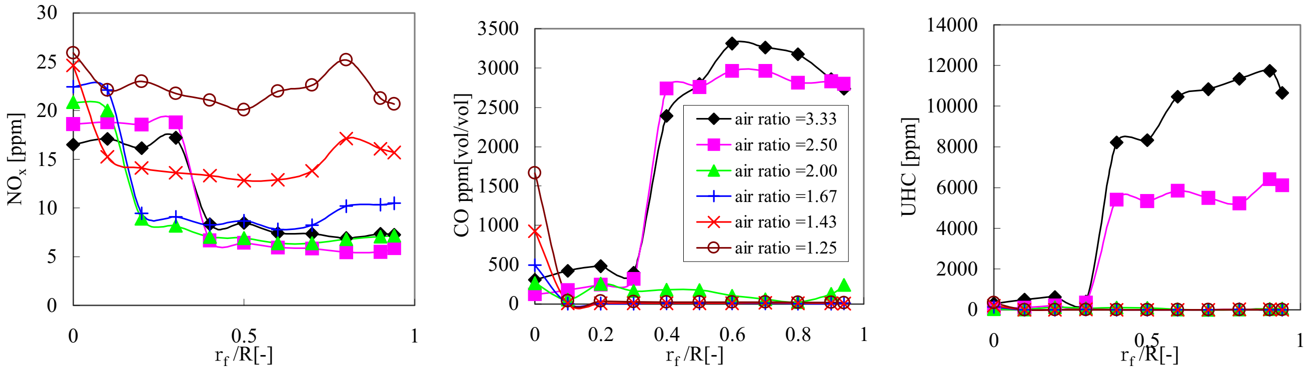


(a) Case of fuel injection at the center

(b) Case of fuel injection at 0.67 of $r_f$/R

(c) Case of fuel injection at 0.94 of $r_f$/R

Fig. 7 UHC emission characteristics as the function of air ratio for various flow rate



(a) $NO_x$ emission

(b) CO emission

(c) UHC emission

Fig.8 Emission characteristics as the function of fuel injection position $r_f$/R for various air ratios
(Fuel nozzle diameter: $D_f$=6.0mm)

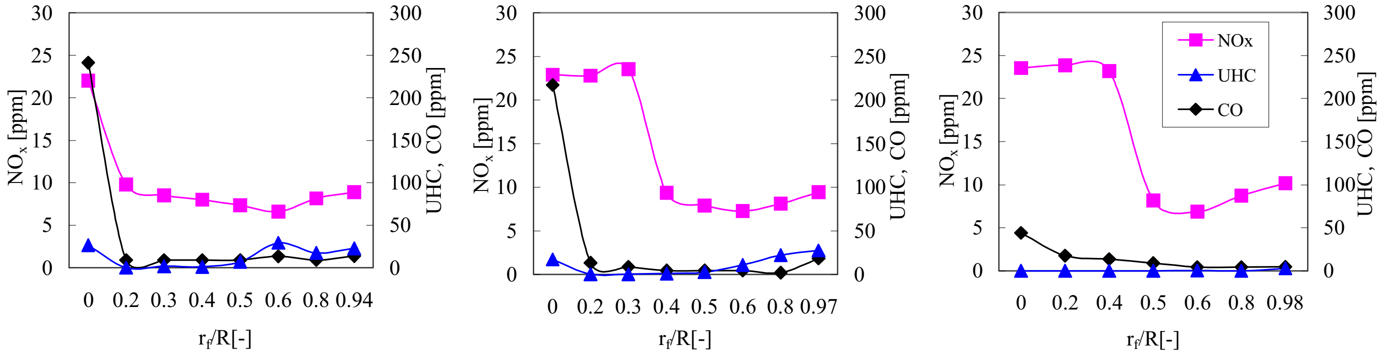
fuel injection around the central position as shown in Fig. 8(a). But at a high air ratio condition more than 1.67, the $NO_x$ emission reduces abruptly when fuel injected from the position outside of 0.2 or 0.3 of $r_f/R$ and changes little according to the shift of the injection port.

CO and UHC emissions are shown in Figs. 8(b) and (c), which indicate both CO and UHC increase abruptly in case of air ratio under 2.50 when the fuel injection position shifts to the outside of 0.3 of $r_f/R$. From the experimental results, the operating condition of air ratio higher than 2.50 produces too much unburned ingredients instead of low value $NO_x$ emission when fuel injected from the outer position, which is probably caused by partial blow-off in an intense turbulent field at a low air ratio condition.

### Effects of Fuel Jet Momentum

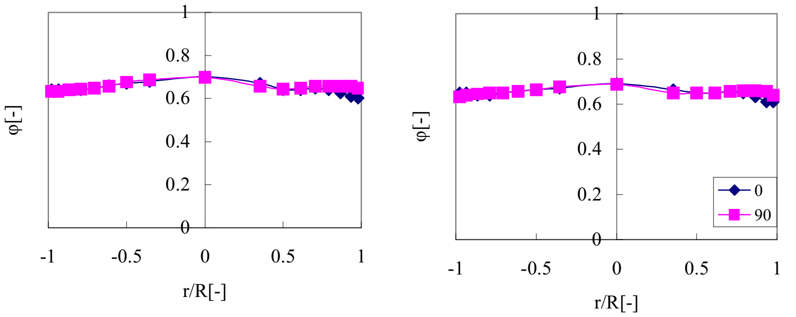
When the fuel injection port is exchanged to a smaller diameter one, the fuel jet momentum can be increased at a same fuel flow rate. As shown in Figs. 9(a), (b) and (c), as the port diameter decreases from 6 mm to 3 mm, the injection position where $NO_x$ emission immediately changes its value shifts to the outer side direction at air ratio of 1.67. When fuel injected at 0.67 or outer side of $r_f/R$, $NO_x$ emission is almost the same value. In that case, fuel diffuses sufficiently in the air flow and the diameter of fuel injection port, that is, the fuel jet momentum does not influence fuel diffusion in the air flow as shown in Fig. 10(a) and (b).

However, the emissions of unburned ingredients, CO and UHC, are insensitive to the fuel injection position in this case. The reason why the $NO_x$ emission characteristics are influenced by the fuel jet



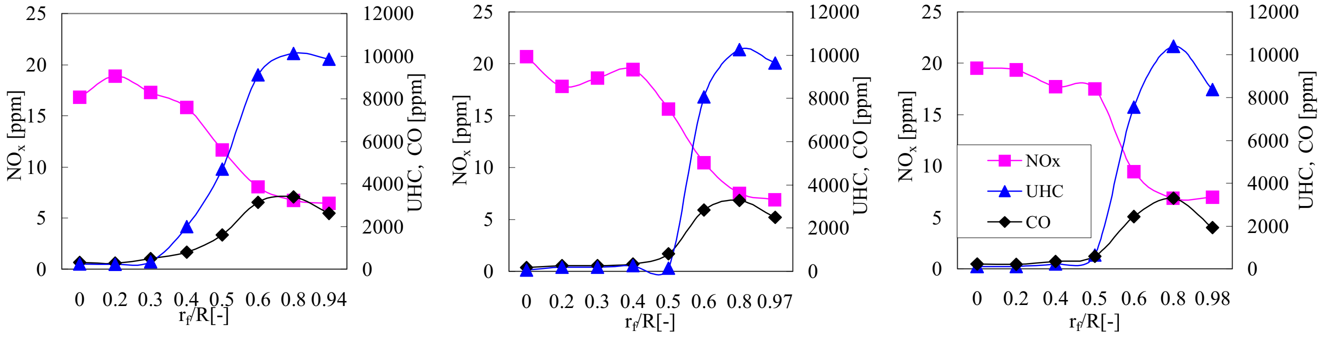
(a) Emission for 6 mm of $D_f$ (b) Emission for 4 mm of $D_f$ (c) Emission for 3 mm of $D_f$

Fig. 9 NOx, CO and UHC emissions of fuel port at fuel/air ratio of 1.67 as the function of radial injection position for three different diameters



(a) Case of fuel port of 6 mm in diameter (b) Case of fuel port of 3 mm in diameter

Fig. 10 Radial distributions of equivalence ratio along the two right-angled diameter for different fuel port diameters (fuel injected at 0.67 of $r_f/R$)



(a) Emission for 6 mm of $D_f$ (b) Emission for 4 mm of $D_f$ (c) Emission for 3 mm of $D_f$

Fig.11 $NO_x$, CO and UHC emissions at air ratio of 3.33 as the function of radial injection position for three fuel port diameter $D_f$

momentum may be expected as the fuel jet injected from a larger port set in the inside position is easy to spread out before reaction starts into the whole swirling air flow, but fuel injected from a smaller port set in the inside non-turbulent position will directly penetrates into the air flow and reacted in a locally rich condition. Figs. 11(a), (b) and (c) indicate $NO_x$, CO and UHC emissions for three cases of different fuel port diameters at air ratio of 3.33. At these cases, all emissions show different tendencies from those of lower air ratio condition case and CO and UHC emissions increase when fuel injected from outer side position, but the emission characteristics are hardly influenced by the fuel injection port diameter. The increase of unburned ingredients in case of fuel injection at the outer position may be caused by the flame quenching of lean mixture by the intense turbulence.

## CONCLUSION

A new type diffusion combustor was tried to verify the emission characteristics and combustion stability for various conditions using a simple experimental model, where fuel is injected into a strong swirling airflow and mixes immediately with air to realize a near-premixed combustion. The results obtained by a series of experiments can be summarized as follows.

(1) Combustion is very stable even in a very high air ratio and/or high flow rate condition.

(2) When fuel is injected at an outer radial position, $NO_x$ emission shows a very low $NO_x$ emission at a air ratio higher than 1.67 (0.6 in equivalence ratio) by sufficient mixing of fuel and air caused by turbulent shear flow, but CO and UHC emissions increase when the air ratio is too high.

(3) When fuel is injected at the center or near the center, $NO_x$ emission becomes high because of insufficient mixing of fuel and air in the central region of a low velocity and weak turbulence.

(4) When the airflow rate is too low, $NO_x$ emission indicates high value because of insufficient mixing of fuel and air in a low velocity flow field.

(5) When the fuel jet momentum becomes high, $NO_x$ emission becomes high even in case of fuel injection at the outer position. It is probably because fuel injected by a large momentum will reach to the downstream reacting region before sufficient mixing with air.

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