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# An Experimental Study on Combustion Processes and $NO_x$ Emission Characteristics of the Air-Staged Burner

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The combustion processes and emission characteristics in air-staged burner have been experimentally studied. The light fuel oil doped with pyridine($C_5H_5N$) is used to investigate the fuel $NO_x$ emission characteristics. Experiments are carried out for a wide range of operating conditions of single-staged and multi-staged burner. The detailed discussions are made for the flame structure of the air-staged burner as well as effects of excess air ratios, staged air flow percentage, and spray conditions on flame pattern and $NO_x$ emission characteristics.

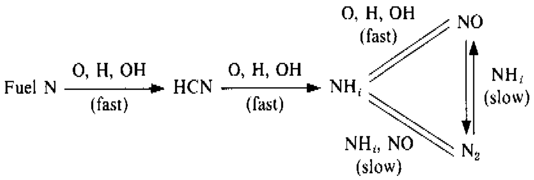
**Key Words :** Air-Staged Burner, Thermal $NO_x$, Fuel $NO_x$, Spray Combustion

## 1. Introduction

Emissions of oxides of nitrogen($NO_x$) during the combustion of biomass and fossil fuels have wide ranging effects on the environment. These effects include the formation of acid rain and photochemical smog, production of tropospheric ozone, and depletion of stratospheric ozone.

Approaches for controlling nitrogen oxide emissions from combustion sources can be divided into combustion techniques and post-combustion methods. Since $NO_x$ emissions are greatly influenced by the precise combustion conditions, emission control by modifying combustion process is the most desirable way. In terms of reaction path(Bowman, 1975, 1992) of NOx formation and destruction, in fuel-lean flames, nitrogen oxides are formed by the attack of O and OH radical on molecular nitrogen($N_2$). In a fuel-rich flame, $NO_x$ are formed by capturing $N_2$ with hydrocarbon radicals, and by pyrolysis and oxidation of heterocyclic nitrogen compounds in fuel oils and coals. In the combustion of fuel containing nitrogen, the fuel $NO_x$ mechanism plays a crucial role in $NO_x$ formation.

The fuel-nitrogen chemistry may be described schematically by



Any nitrogen-containing fuel species is converted to HCN in the flame and this very fast step is followed by the fast conversion of HCN to $NH_i$($i=0, 1, 2$). $NH_i$ then either forms NO by reaction with an O or OH radical or reacts with NO to $N_2$. The reactions leading to $N_2$ formation is much slower than those leading to NO. Since the path favoured for the reaction of the $NH_i$ radical is determined by the flame conditions including temperature and equivalence ratio, the multiply staged combustion techniques such as fuel-staged and air-staged combustion can be effectively applied for in-flame fuel $NO_x$ reduction. Fuel-staged combustion systems are operated with a slightly lean first stage, where $NO_x$ production is high, and a consecutive reduction zone, where additional fuel is injected to achieve fuel-rich conditions for the reduction of $NO_x$ from the primary combustion zone. In the air-staged combustion systems(Togan et al., 1992 ; Beer, 1996 ; Smart et al., 1988), the multiply staged combus-

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tion air is required to establish the fuel-rich/fuel-lean sequencing favorable for conversion of fuel bound nitrogen to $N_2$. The air-staged low $NO_x$ burner utilizes burner aerodynamics to control the fuel/air mixing processes whereas most of conventional burners are designed to achieve a high turbulent mixing rate and the intense combustion in the primary reaction zone. The challenging issue in optimally controlling the multi-staged combustor is to produce a fuel-rich flame zone close to the injector which provides sufficient residence time for fuel pyrolysis and conversion of fuel bound nitrogen to $N_2$ as well as to vigorously mix the rest of combustion air and the remaining fuel to ensure complete combustion.

In the present study, the sequence of experimental work were carried out for identifying the optimal combustion conditions for achieving a low $NO_x$ emission in an air staged oil burner. In order to investigate the effects of fuel nitrogen content on $NO_x$ emission characteristics (Gerhold et al., 1979 ; Martin and Dederick, 1977 ; Takagi et al., 1979), fuels are used as the light fuel oil with pyridine. Experiments are performed for the various excess air ratios, air flow percentage at each stage, and spray conditions in the single-staged and multi-staged burners. The comparative emission characteristics for the single-staged and multi-staged burners has been made. Effects of excess air ratio, air flow percentages and fuel injection pressures are discussed in detail.

## 2. Experimental

In this study, the experiment is carried out for the gun-type single-staged burner and the multi-staged burner. In the multi-staged burner, the flame structure and the $NO_x$ emission characteristics can be controlled by adjusting the primary, secondary, and tertiary air flow rates. The multiple air-staged burner usually utilizes the two-staged type. However, in this experimental study, the three staged burner is used for generating the lengthy flame encountered in the industrial high-capacity burner as well as for investigating the combustion characteristics in the wide range of

**Table 1** Concentration of fuel nitrogen.

| (%) | Light fuel oil | Light fuel oil doped with pyridine | | |
|---|---|---|---|---|
| N | 0.02 | 0.3 | 0.6 | 1.21 |

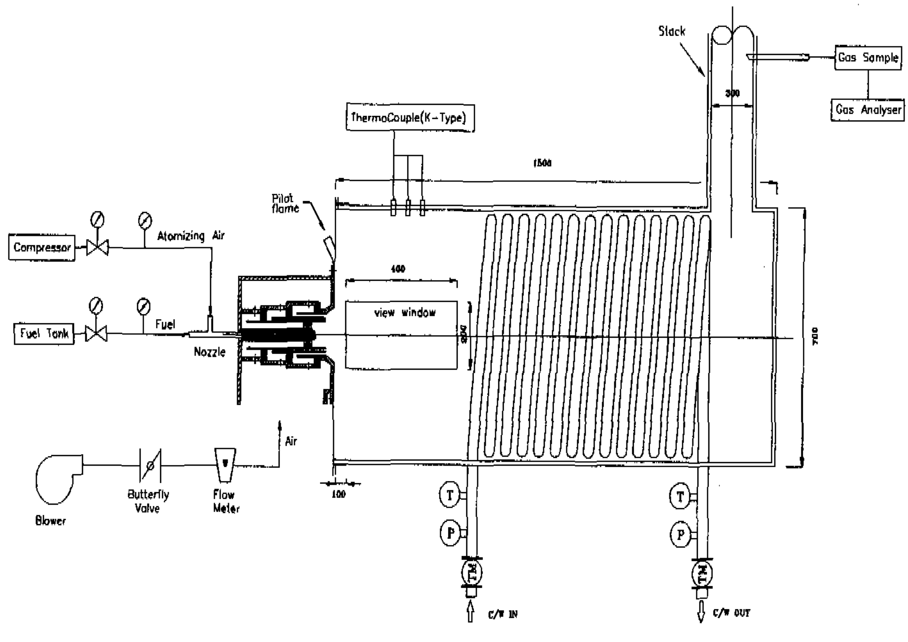


**Fig. 1** Schematic diagram of experimental apparatus.

operating conditions.

The liquid fuels are used as the light fuel oil and the light fuel oil doped with pyridine ($C_5H_5N$). The concentrations of N in the liquid fuels are given in Table 1.

In this study, the liquid fuel is atomized by an air-assisted twin fluid injector. The Malvern system is used to measure the Sauter Mean Diameter (SMD). The spray type of this atomizer is solid cone, and the spray angle is 40°~50°. In these solid-cone sprays, the fuel droplets are more densely loaded along the centerline. By increasing injection pressure, the spray angle decreases, and injection velocity and the turbulent mixing increases.

Figure 1 shows the schematic arrangement of experimental apparatus for the multi-staged burner. The combustion system consists of burner, fuel and atomizing air supply, and blower. Around the furnace wall, the water pipe is installed for cooling the furnace wall and controlling the furnace temperature. The U tube manometer is used to check the pressure of combustion chamber. The K-type and R-type thermocouples are used to measure the wall temperature and the temperature distribution of the flame fields. The CO and $NO_x$ concentrations of the combustion gas sampled at the exhaust are determined by a gas analyzer(Greenline MK2) mounted at stack. The quartz window is installed to visualize the flame field. The pilot propane flame is utilized to initially ignite the two-phase mixture and stabilizes the spray flame field. In twin-fluid nozzle atomizer, the atomizing air is supplied by the compressor and the liquid fuel injected through a pumping motor. The combustion air is supplied by the blower and the air flow rate is regulated by the butterfly valve. In this multi-staged burner, the air flow rate in each stage is adjusted by the separately installed flow control valves. The various excess air ratios are obtained by varying the total air flow rate while maintaining the constant fuel flow rate.

Figure 2 shows the detailed configuration and dimensions of the multi-staged burner. The combustion air passing through primary, secondary, and tertiary air nozzles is injected into the combustion chamber for creating optimally separated fuel-rich and fuel-lean combustion stages and swirler in primary nozzle is installed for stabilizing flame field. This air-staged burner is well suited to fuel-$NO_x$ control since it provides the

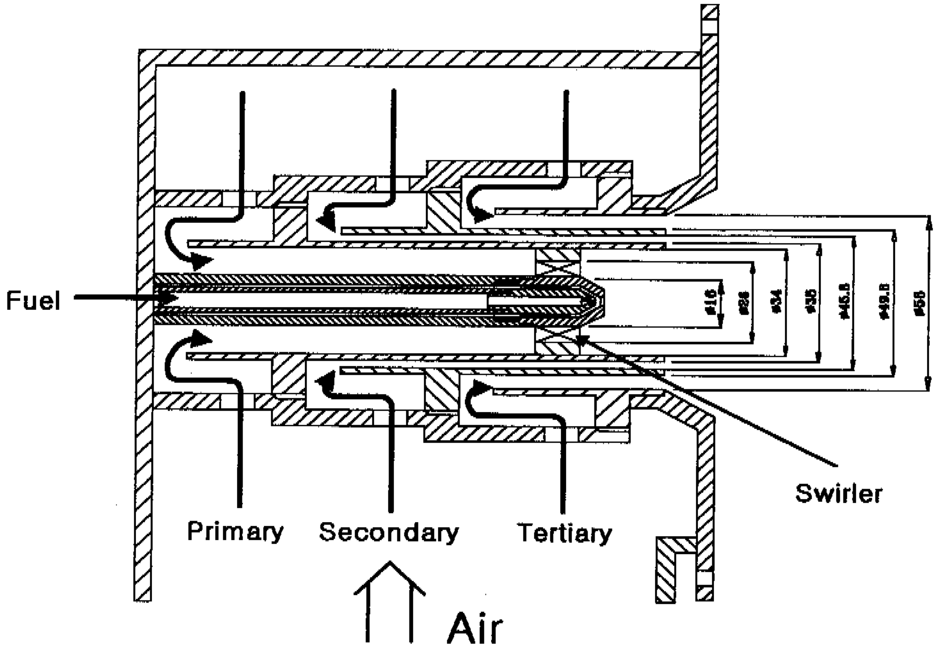


**Fig. 2** Configuration and dimensions of the multi-staged burner.

separated fuel-rich and fuel-lean flame zones and the resulting combustion processes allow the sufficient residence time for the reduction of fuel-nitrogen to $N_2$ while maintaining the high combustion efficiency.

Experiments were done for the following range of operating conditions:

| | |
|---|---|
| Fuel mass flow rate | 15 kg/hr |
| Fuel jet angle | 40°~50° |
| Percentage of primary, secondary, tertiary air | 0~100% |
| Swirl number in primary nozzle | S=0.82 |
| Combustion air temperature | 50℃ |
| Excess air ratio($\lambda$) | 1.1~1.4 |
| Fuel droplet size | *Condition A, B* |

Based on these various operating conditions, effects of excess air ratios, staged air percentages, and spray conditions on $NO_X$ emission and flame pattern are experimentally investigated.

## 3. Results and Discussions

In order to investigate the combustion processes and emission characteristics in single and multi-staged burner, the sequence of experiments were carried out for a wide range of operating conditions. First we studied the CO and $NO_X$ emission characteristics in case of using a light fuel oil. The liquid fuel is atomized at *Condition A* given in Table 2. When a light fuel oil containing the little fuel nitrogen was used without any additives, it can be assumed that the $NO_X$ emission is strongly influenced by the thermal $NO_X$ mechanism and partially contributed by the prompt $NO_X$ mechanism.

The CO and NO emission characteristics are shown in Fig. 3 and Fig. 4.

In case of the single-staged burner, the CO emission maintains the approximately same level slightly lower than 20 ppm for the wide range of excess air ratios. However the multi-staged burner with the large portion of annular nonswirling air flow has distinctly different CO emission characteristics, in which CO gradually increases with increasing excess air ratio due to the elevated quenching effect and the reduced residence time. Since the excess air ratio in the normal operating condition is usually lower than 1.1, the CO emission level lower than 100 ppm in the multi-staged burner is not quite serious in the practical applications. Furthermore these CO emissions could be reduced by installing a relevant swirler in the tertiary nozzle.

**Table 2** Experimental conditions of air-assisted atomizer.

| | Fuel injection pressure ($kg_f/cm^2$) | Atomizing air pressure ($kg_f/cm^2$) |
|---|---|---|
| Condition A | 0.40 | 0.40 |
| Condition B | 0.65 | 0.85 |

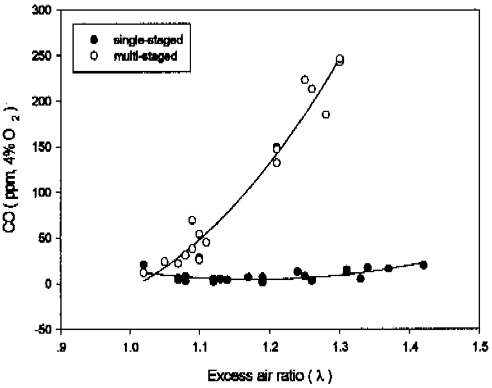


**Fig. 3** CO emission versus excess air ratio in single and multi-staged burner.

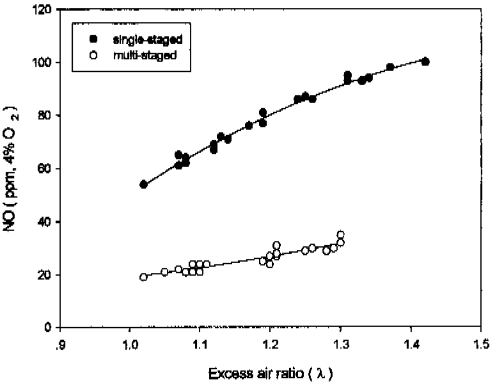
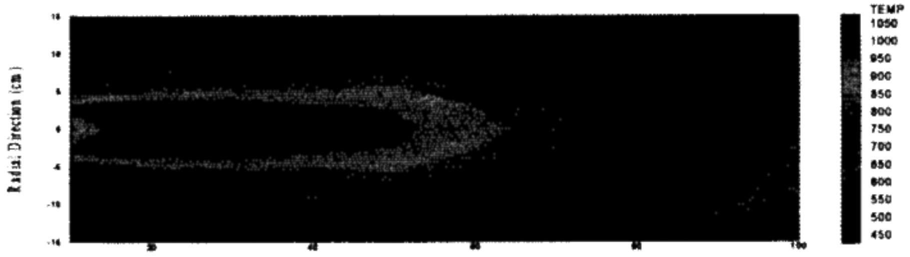


**Fig. 4** NO emission versus excess air ratio in single and multi-staged burner.

In terms of the NO emissions, the emission level for two burners increases by increasing the excess air ratio. Compared to the multi-staged burner, the NO emission in the single-staged burner is relatively sensitive to the variation of excess air ratio. It can be clearly seen that the multi-staged burner maintains the much lower NO emission level for the given excess air ratio. For the single-staged burner, increase in the excess air ratio results in enhancing the turbulent mixing and intensifying the combustion process. On the other hand, the multi-staged burner has the complex reacting flow structure which consists of the upstream fuel-rich zone and the downstream fuel-lean flame zone. By increasing the primary air flow rate, the turbulent mixing is enhanced and the combustion process in the swirling flame zone becomes intense. Thus increase in aeration possibly increases the NO emission. However, in the multi-staged burner, the relatively small air mass flow is injected by passing through the primary air nozzle with a swirler and the large portion of air mass flow is injected in the secondary and tertiary air nozzle. As a result, the turbulent fuel/air mixing in the primary combustion zone is significantly suppressed mainly due to decrease in the primary swirling air flow and partially due to the laminarization effect(Toqan et al., 1992 ; Beer, 1996) arising from the density-variable rotating flow field. The laminarization of density-stratified turbulent rotating flows depends on the stratification parameter known as the modified Richardson number(Toqan et al., 1992 ; Beer, 1996).

$$R_i^* = \frac{\left(\frac{1}{\rho}\right)\left(\frac{\partial \rho}{\partial r}\right)\left(\frac{\omega^2}{r}\right)}{\left(\frac{\partial u}{\partial r}\right)^2}$$

Here $\rho$, $u$, $\omega$ and $r$ denote density, axial velocity, rotational velocity, and radial coordinate, respectively. The modified Richadson number represents the ratio of centrifugal forces stabilizing turbulence in the density-variable rotating flow to the shear force generating turbulence. In the density-stratified rotating flows, stabilization effects begins to act for $R_i^* > 0$, but for $R_i^* > 1$ the stabilizing force becomes dominant and results in damping turbulence. In the swirling reacting flow of the present air-staged burner, we expect the stabilization effect associated with the modified



(a) Single-staged burner

(b) Multi-staged burner

**Fig. 5** Flame temperature contours in single and multi-staged burner.

Richardson number to be of secondary importance in the inner fuel-rich reaction zone, but to be important in the boundary of primary and secondary jet with the higher density gradient. Therefore decrease in the primary air flow and the stabilization effect in the density-variable rotating flow eventually create a lengthened fuel-rich flame zone which can provide sufficient residence time for fuel pyrolysis. and conversion of fuel nitrogen to $N_2$. The secondary and tertiary air flow contributes to the continuous mixing of the remaining air and the remaining fuel for maintaining the high combustion efficiency as well as the formation of fuel-rich and fuel-lean flame zone. Therefore, the detailed flame structure of the multi-staged burner is considerably influenced by the flow rate of primary, secondary, and tertiary air jet. Since the concentration(0.02 %) of fuel-bound nitrogen in a light oil is so low, the NO emission in the light oil/air combustion process is mainly controled by the thermal $NO_x$ mechanism. Thus these experimental results suggest that the air-staged combustion technique could be useful to reduce the thermal $NO_x$ emission by widely distributing the heat release rate in the combustion chamber.

Figure 5 shows the measured temperature contours in the single-staged and multi-staged burner at the excess air ratio of 1.1 and the spray condition(*Condition A*). Temperatures in the flame field was measured by the R-type thermocouple.

The single-staged burner creates the much shorter flame with the relative high temperature flame zone while the multi-staged burner yields the lengthened flame field containing two flame zones. These two flame zones consist of the fuel-rich flame zone and the fuel-lean flame zone. The flame length of the single-staged burner and multi-staged burner are approximately 50～60 cm and 80～100 cm for the spray conditions and the excess air ratio tested in the present study. The peak flame temperature of the multi-staged burner is 200℃ lower than that of the single-staged burner. Obviously these lower temperature in the lengthened flame zone results in the reduction of the thermal $NO_x$ formation.

Next we investigated the fuel $NO_x$ emission processes by adding pyridine($C_5H_5N$) into the light fuel oil. Measurements were performed for various fuel N contents(1.21%, 0.6%, 0.3%, 0.02%). 0.02% fuel nitrogen concentration corresponds to the pure light fuel oil. Figures 6 and 7 shows the NO emission versus the excess air ratio for four fuel-N concentrations in single and multi-staged burner.

The NO emission is noticeably increased by increasing the fuel-nitrogen concentration. These experimental results clearly indicate that the fuel nitrogen is a important source of NO emission. In comparison with the NO emission of the single-staged burner, the multi-staged burner produces the much lower fuel $NO_x$ emission. This is caused by the sufficient residence time for fuel pyrolysis and fuel $NO_x$ conversion to $N_2$ in the long and

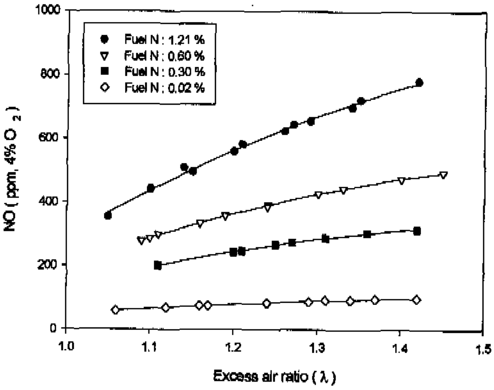


**Fig. 6** NO emission versus excess air ratio in single -staged burner.

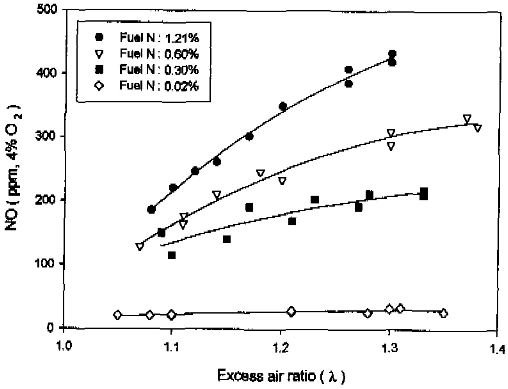


**Fig. 7** NO emission versus excess air ratio in multi -staged burner.

lazy fuel-rich flame zone. These results demonstrate that the multi-staged burner is quite capable of reducing fuel $NO_x$ as well as thermal $NO_x$.

In order to investigate the effects of the percentage of combustion air flow rates of primary, secondary and tertiary jet on the emission characteristics, experiments are performed for four combinations of combustion air flow rates, (21.9%, 31.8%, 46.3%), (19.6%, 38.7%, 41.7%), (18.5%, 41.7%, 39.8%), and (18%, 42%, 40%) at the spray condition(*Condition A*) and the 0.6% fuel-N concentration. Experimental results shown in Fig. 8 suggest that the NO emission level can be reduced mainly by decreasing the primary air flow rate, partially by increasing the secondary air flow rate, and marginally by decreasing the tertiary air flow rate. Decrease of NO emission corresponds to the suppressed turbulent fuel/air mixing in the primary combustion zone which is caused mainly due to decrease in the primary swirling air flow and partially due to the laminarization effect(Toqan et al., 1992; Beer, 1996) in the radially density-variable rotating flow.

Figure 9 shows the flame shape for four combinations of combustion air flow rate. These visualized results clearly show the flame field of the multi-staged burner consists of the upstream fuel-rich flame zone and the downstream fuel-lean zone. These results indicate that increase in the interval between the fuel-rich flame and the fuel-lean flame can reduce the $NO_x$ emission due to the increased residence time.

Finally, effects of injection pressure on combustion characteristics and pollutant emission are investigated for two burners and two spray conditions. In this study, the same mass flow rates of liquid fuel are maintained for *Condition A* and *B* given in Table 2. Figure 10 shows the centerline(r =0.0cm) and radial(x=5.0cm) distribution of SMD for two spray conditions. Compare to the lower fuel and atomizing air pressure case(*Condition A*), the higher fuel and atomizing air pressure case(*Condition B*) produces the much smaller droplets in the combustion chamber. In the

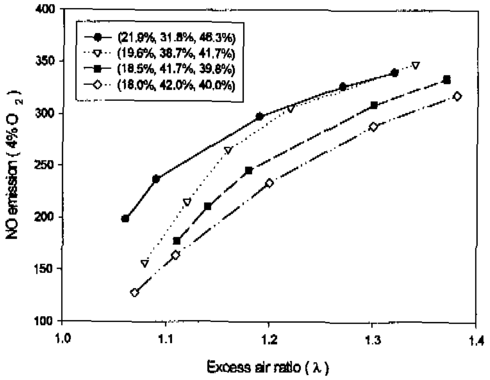
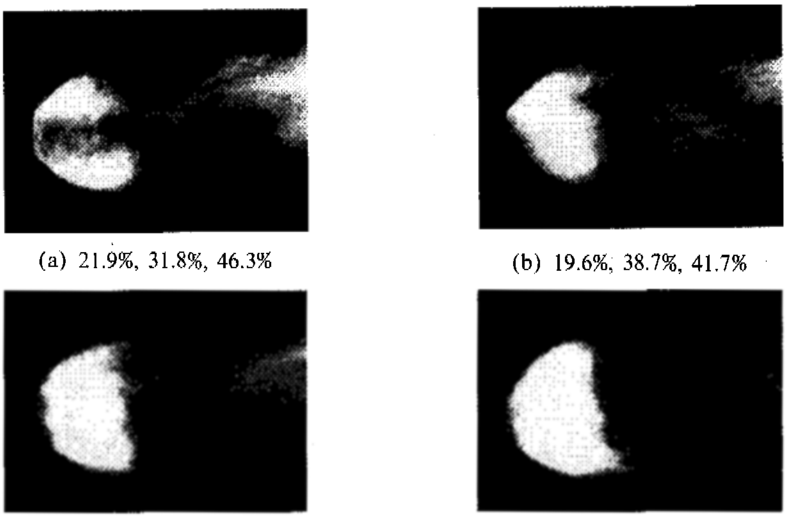


**Fig. 8** Effects of staged flow percentage on NO emission.



(a) 21.9%, 31.8%, 46.3%

(b) 19.6%, 38.7%, 41.7%

(c) 18.5%, 41.7%, 39.8%

(d) 18.0%, 42.0%, 40.0%

**Fig. 9** Photographs of flame shape for 4 flow percentages [$\lambda=1.1$]

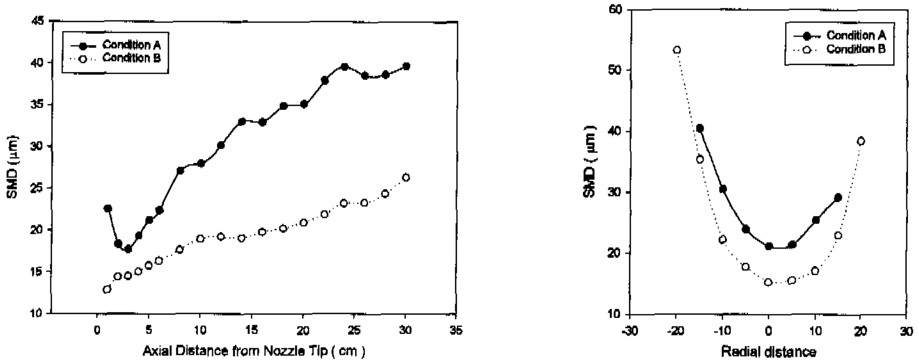


**Fig. 10** Axial and radial distribution of SMD.

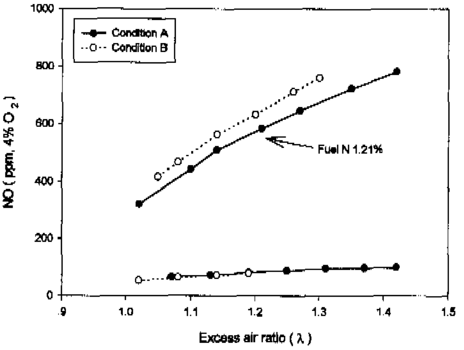


**Fig. 11** Effects of spray conditions on NO emission in single-staged burner.

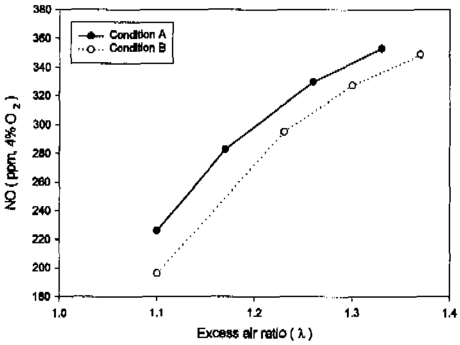


**Fig. 12** Effects of spray conditions on NO emission in multi-staged burner. [(19.6%, 38.7%, 41.7%)]

near injector region with the large interphase relative velocity, SMD rapidly decreases due to the droplet breakup process. However, along the further downstream regions with the progressively decreasing relative velocity, SMD gradually increases mainly due to the droplet collision process. Figure 11 shows the effects of spray conditions on the NO emission in the single-staged burner. In case of using the light fuel oil, the corresponding thermal $NO_x$ emission is almost insensitive to the spray conditions. These results imply that variation in injection pressure does not noticeably modify the flame temperature field in the single-staged burner and the peak flame temperature is relatively low. As shown in Fig. 11, for the light fuel oil doped with pyridine (fuel N 1.21%), the higher injection pressure case (*Condition B*) having the smaller SMD distribution and the more intense turbulent mixing produces the much higher fuel NO distribution. In the single-staged burner, most of smaller droplets are trapped in the toroidal vortex driven by the primary swirl and they are quickly evaporated and burned in the turbulent mixing dominant region. Thus, *Condition B* corresponding to the shorter droplet lifetime, and the faster turbulent mixing rate doesn't provide enough time for fuel $NO_x$ conversion to $N_2$. For *Condition A* having the relatively large droplets and the relatively weak turbulent mixing, the evaporation time becomes longer and the fuel/air mixing process is much slower. This situation can establish the more fuel-rich lengthened flame which allows the relatively long residence time for fuel-N conversion to $N_2$. Thus, in the single-staged burner, the lower injection pressure case produces the lower NO emission level for a wide range of excess air ratios.

Figure 12 shows the effects of spray condition on the NO emission in the multi-staged burner. For the light fuel oil doped with pyridine, unlike

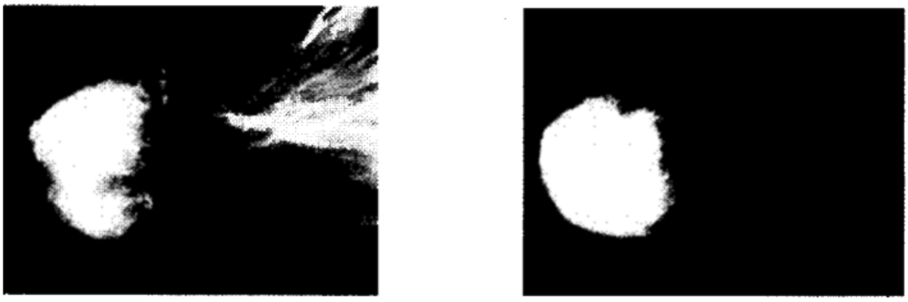


**Fig. 13** Photographs of flame shape for two spray conditions in multi-staged burner.
[(19.6%, 38.7%, 41.7%), $\lambda=1.1$]

the single-staged burner, the higher injection pressure case (*Condition B*) corresponding to the smaller SMD distribution fields produces the lower NO emission. In the multi-staged burner, *Condition B* creates the highly fuel-rich flame close to injector because the droplets evaporates rapidly and decrease in the swirling primary air flow significantly suppresses the turbulent air/fuel mixing. As a result, the less intense and lengthened flame is formed and it allows enough residence times for conversion of fuel bound nitrogen to $N_2$. On the other hand, *Condition A* having the relatively larger droplets produces the fuel-rich flame field with the relatively low equivalence ratio because the spray field with the larger SMD distribution is slowly evaporated and some of the larger droplets possibly penetrate the recirculating flame zone. Thus, the resulting widely distributed fuel vapor mixes with combustion air and the lean flammable mixture could be established closer to the upstream flame. Figure 13 shows the spray flame fields for the multi-staged burner and these results partially explain the effects of injection pressure on the spray flame structure and NO emission characteristics. Compared to the higher injection pressure case (*Condition B*), the lower injection pressure case (*Condition A*) has the much shorter interval between the fuel-rich flame and the fuel-lean flame and it doesn't provide enough residence time in the fuel-rich zone. Therefore, in case of the multi-staged burner, the lower injection pressure corresponds to the relatively high NO emission level for the wide range of excess air ratios.

## 4. Conclusion

Based on the experimental results of single and multi-staged burner, the following conclusions can be drawn.

(1) In case of the single-staged burner, the CO emission maintains the approximately same level for a wide range of excess air ratios. However the multi-staged burner has the distinctly different CO emission characteristics, in which CO gradually increases with increasing the excess air ratio due to the elevated quenching effect.

(2) The NO emission level for single and multiple staging burner increases by increasing the excess air ratio. The NO emission in the single-staged burner is relatively sensitive to the variation of excess air ratio and the multi-staged burner produces the much lower fuel $NO_x$ emission.

(3) In the multi-staged burner, the turbulent fuel/air mixing in the primary combustion zone is significantly suppressed mainly due to decrease in the primary swirling air flow and partially due to the laminarization effect in the density-variable rotating flows. These aerodynamic effects create a lengthened fuel-rich flame zone which can provide sufficient residence time for fuel pyrolysis and conversion of fuel nitrogen to $N_2$. The NO emission in the air-staged burner can be reduced mainly by decreasing the primary air flow rate and partially by increasing the secondary air flow rate.

(4) When the light fuel oil is used, the NO emission of the single-staged burner is almost

insensitive to the fuel injection pressure. In case of the single-staged burner utilizing the light fuel oil doped with pyridine, the lower injection pressure case produces the lower NO emission level. However, in case of the multi-staged burner, the lower injection pressure corresponds to the relatively high NO emission level for a wide range of excess air ratios.

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