An Experimental Study on Combustion Dynamics and NO_x Emission of a Swirl Stabilized Combustor with Secondary Fuel Injection*

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Abstract

To investigate the effects of flow rate, diameter and offset of secondary fuel injection on combustor noise level, pressure fluctuation and NO_x emission, four types of injectors were examined in a swirl-stabilized combustor for overall equivalence ratio (ϕ) of 0.7 ~ 0.9 and flow rate of secondary fuel (Q_{sec}) from 0.6 to 4.2 L/min. As for the reference injector used in previous related studies, secondary fuel injection of 3.0 L/min is the best condition for the reduction of pressure fluctuation and combustion noise with tolerable NO_x emission. For lower secondary fuel rate of 1.8 L/min, reduction of the injection diameter of reference injector results in a better performance in terms of combustion noise and pressure fluctuation reduction. By the secondary fuel injection with offset, NO_x emission shows lower values than those of the injections without offset for the whole range of equivalence ratios. Spectral analysis of pressure fluctuations revealed that larger amount of secondary fuel ($Q_{\text{sec}} \geq 3.0$ L/min) by the injectors with injection offset induce a lot of new modes in the wide range of frequency. For near stoichiometric operating condition ($\phi \geq 0.85$) by higher amount of secondary fuel injection with offset ($Q_{\text{sec}} = 4.2$ L/min), the flame lifts over the swirl injector, NO_x emission decreases and instability modes appear in a frequency range lower than those of the injection without offset. The results also suggest that the emission index is deeply related to flame lift-off and the dominant mode of instability.

Key words: Secondary Fuel Injection, Swirl Nozzle, Pressure Fluctuation, NO_x Emission, Instability Mode

1. Introduction

Reduction of NO_x emission should be considered as a major factor in the design process of modern gas turbine engines to meet the stringent regulations on permissible emission level. Lean premixed combustion decreases the adiabatic flame temperature and consequently reduces the production rate of NO_x emission which is highly temperature dependent⁽¹⁾. However, in this operating range, the appearance of thermo-acoustic instabilities becomes a major concern. Generally, thermo-acoustic oscillations occur due to the coupling between the flame heat release behavior and oscillations that arise in the combustor flow field⁽²⁾. In this condition the resulting coupled system dynamics emerges as high-amplitude oscillations of both heat release and flow field variables. The resultant flow

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and structural vibrations have adverse effects on the performance⁽³⁾⁻⁽⁶⁾ and can substantially reduce hot section part life⁽⁷⁾. Based on pioneering works of Rayleigh⁽⁸⁾, one may control combustion oscillations by simply introducing an energy source out of phase with fluctuation of the heat release rate. However, a detailed understanding of the combustion oscillation and instability mechanism is necessary for an effective and robust active control of combustion.

Secondary fuel injection is considered to be a promising approach for combustion control due to two reasons: one advantage of this method is that successful combustion control can be possible by using a considerably small amount of energy, and the other merit is that it reduces the actuator requirements. These advantages make the secondary fuel injection a desirable choice for suppression of pressure fluctuations and prevention of lean blowout. Lee et al.⁽⁹⁾ studied the effects of the secondary fuel injection location on combustion control effectiveness. In their work, injection with 0-degree angle from the central hub showed the best performance in suppression of combustor pressure oscillation levels. Tachibana et al.⁽¹⁰⁾ conducted a series of experiments of steady secondary fuel injection using five types of injectors. They investigated the effects of the angle, location and amount of the injection on the level of combustor pressure oscillations. Choi et al.⁽¹¹⁾ applied open-loop controls with a 45-degree secondary fuel injection to the combustion driven oscillations occurring in a swirl-stabilized premixed combustor and investigated the effects on pressure oscillations, noise levels and NOx emissions. They have revealed that, due to the modification of local flame structure by the secondary fuel injection, combustion noise and NOx emission can be reduced simultaneously. In the same way, to investigate the mechanism of combustion noise reduction by secondary fuel injection, planar laser induced fluorescence (PLIF) measurements⁽¹²⁾ and simultaneous measurements of stereoscopic particle image velocimetry (SPIV) together with pressure fluctuation of combustor⁽¹³⁾ were conducted for methane-air turbulent premixed flames in the same swirl-stabilized combustor as used in the study of Choi et al.⁽¹¹⁾ and the present work. The structures both in the recirculation zone and flame zone were investigated and mean progress variable was evaluated from the results of OH fluorescence intensity⁽¹²⁾. It was shown that secondary fuel injection leads to suppression of fluctuations of the high temperature gas in the recirculation zone. Tanahashi et al.⁽¹²⁾ also suggested that secondary fuel injection reduces the Reynolds stress and entropy terms associated with dissipation of the turbulent energy in the acoustic sound source, due to control of the turbulent velocity field. Suppression of large-scale vortical motion was also reported⁽¹³⁾ to be significant for reduction of combustion noise.

It is also important to understand the relations among the pressure oscillations, combustion noise and NOx emission level. De Zilwa et al.⁽¹⁴⁾ showed that for premixed methane-air flames in ducted plane sudden-expansion combustor, the modulation of pressure fluctuation is associated with low-frequency movement of flame front. Ballester et al.⁽¹⁵⁾ studied the influence of burner aerodynamics on the characteristics of the flame by means of detailed measurements and by analyzing the pressure spectra in a laboratory gas-fired furnace. They showed that variations in swirl intensity affect the emissions due to changes in the mixing pattern. Poppe et al.⁽¹⁶⁾ examined the effect of oscillations on NOx concentrations in ducted bluff-body stabilized flames and at the exit plane of a sector of a gas-turbine combustor. They suggested that mean NOx concentrations near stoichiometry would decrease with increase of the amplitude of oscillations. Keller and Hongo⁽¹⁷⁾ also reached similar conclusion, based on their measurements of velocity and temperature in ducted flames. The mechanism responsible for low NO formation in their study was reported to be a short residence time at high temperature. These points encourage ones to do a parametric study on the effects of secondary fuel injection on NOx formation level in the range between lean and near stoichiometric operating condition. By changing the design parameters of secondary fuel injectors and the amount of injection, study on the relations

among the pressure fluctuations, combustion noise and NO_x emission level becomes more feasible, considering the visible behavior of the flame shape.

The objective of the present study is to investigate the effects of secondary fuel flow rate, injection diameter and injection offset (with respect to the injector center) on the combustor noise level, pressure oscillations and nitric oxides production level and to study the relations among these combustor parameters. The experiments were carried out by using four different types of secondary fuel injectors with an overall equivalence ratio between $\phi = 0.7$ and 0.9 and different amount of secondary fuel injection rate in the range of $\dot{Q}_{\text{sec}} = 0.6 \sim 4.2$ L/min.

2. Experimental apparatus

In this study, a swirl-stabilized combustor which has been already investigated in other related researches^{(11)-(13), (19)} is used. Figure 1 shows the schematic of the swirl-stabilized combustor and details of swirl burner⁽¹¹⁾. This combustion rig consists of a contraction section, a swirl nozzle section and a combustion chamber. The inner diameter of 120 mm in the contraction section is reduced to 40 mm diameter in the swirl nozzle section. This swirl nozzle has 8 swirl vanes of 14 mm inner diameter and 40 mm outer diameter, inclined 45° from the nozzle axis. The combustion chamber inner cross-section of 120 mm × 120 mm is also contracted to 60 mm × 60 mm on the outlet. The total length of the chamber is 590 mm and a silica glass plate of 120 mm × 170 mm with 5 mm thickness on each side of combustion chamber is used for a relevant optical access. The methane-air premixed gas passes through the swirl nozzle and the flame is stabilized above the swirl vanes.

Fig. 1 Schematics of the swirl-stabilized combustor and details of swirler and secondary fuel nozzle.

Fig. 2 Design of secondary fuel injectors.

Figure 2 illustrates the design of four different types of secondary fuel injectors which were examined in this study. All of these injectors are mounted at the hub of the swirler. The injector type A which has been already used in the previous studies^{(11)-(13), (18)} has 8 injection

holes (ID = 0.6 mm) inclined at 45° to the mainstream direction. To investigate the effect of injection diameter on combustion dynamics and NO_x emission level of the combustor, injector type B with 8 smaller injection holes (ID = 0.4 mm) and the same injection angle of 45° with respect to the mainstream direction was used. The locations of the 8 injection holes for injector types C and D (ID = 0.6 mm) are chosen such that they have a certain offset (Offset = 2.1 mm) with respect to the injector center. The offset direction in injector C is such that the injected fuel opposes the main swirling flow, and can provide varying degrees of interaction with the main swirling flow depending on the secondary fuel flow rate. In contrast to the injector C, the injected fuel with injector type D assists the swirling motion of the main swirling stream inside the combustor. It is noteworthy that the injected fuel with injectors C and D make the same injection angle of 45° with respect to the mainstream direction.

For measuring the pressure fluctuations in the combustion chamber, a pressure transducer (TOYODA, PD104) with water-cooling connector was mounted on the combustor wall at the position 500 mm downstream from the exit of swirl nozzle. Sound level was measured with the sound level meter (ONO SOKKI, LA-1240) which was placed at a distance of 230 mm away from the combustor wall and 500 mm above the exit plane of swirl nozzle, facing one side of the combustor, along the burner axis. The concentration of nitric oxides was measured by a gas analyzer (SHIMADZU, NOA-7000). A water-cooled sampling probe with a 1.0 mm suction hole was used to sample the burned gases at 20 mm upstream of the exit plane in combustion chamber. Since the gas sample was dried before entering the analyzer, concentrations are reported on dry basis. The concentration of NO_x was considered as the sum of the amounts of NO and NO₂.

3. Experimental Conditions

The total flow rate of mixture (Q_m) was adjusted to 300 L/min and pure methane (99.5 % purity) was used as the secondary injected fuel in this study. Based on previous studies on this combustor⁽¹¹⁾, the r.m.s. of pressure fluctuations and noise level show significantly large values between $\phi = 0.7$ and 0.9. The dominant frequencies can be attributed to excitation of a quarter-wave mode of the combustion chamber, assuming the mean temperature of combustor in the range of 1000-1300 K. In this study, experiments with an overall equivalence ratio between $\phi = 0.7$ and 0.9 together with different amount of secondary fuel injection flow rate (Q_{sec}) for a range of 0.6 ~ 4.2 L/min, which is 0.2 % ~ 1.4 % of total mixture flow rate (Q_m) respectively, were carried out. To investigate the effects of secondary fuel flow rate on r.m.s. of pressure fluctuations and NO_x emission level for each overall equivalence ratio, both the secondary and main fuel flow rates were changed at a constant air flow rate to maintain a fixed overall equivalence ratio during the combustor operation.

4. Flame Shapes

Figure 3 shows direct long-time exposure photographs of the methane–air turbulent premixed flames controlled by continuous secondary fuel injection for $Q_m = 300$ L/min, $\phi = 0.90$ and $Q_{sec} = 4.2$ L/min with injectors A, B, C and D. All four flames showed no soot production and burned with a light blue color. By injecting secondary fuel with injectors A and B a tulip-shaped blue flame stabilized near the swirl nozzle. The visible blue flame with the injectors C and D lifted over the nozzle and become relatively uniform and flattened. The intensity of radiation from the blue flames with injectors A and B are more intense and brighter than those with the injectors C and D. In other words, based on the visual observations, the lifted flames with injection offset (i.e., flames with injectors C and D) display a less luminous core than the flames without injection offset. They also exhibit a more fluctuating behavior than flames without injection offset.

Fig. 3 Long-time exposure photograph of methane-air turbulent premixed flame for $Q_m = 300$ L/min, $\phi = 0.90$ and $Q_{sec} = 4.2$ L/min with injectors A, B, C and D.

5. Results and Discussion

Figure 4 shows the variation of the emission index as a function of overall equivalence ratio and secondary fuel injection rate for the injector type A. Regardless of secondary fuel injection rate, the emission index increases with increase of the overall equivalence ratio. Figure 4 also indicates that, in higher equivalence ratios ($\phi > 0.80$), NOx emission decreases for $Q_{sec} = 3.0$ or 4.2 L/min comparing the lower Q_{sec} for the same equivalence ratio. Regarding the level of emission index, there are certain effects that can lead to reduction of NOx formation. These effects include delayed mixing, highly off-stoichiometric conditions and low flame temperatures⁽¹⁵⁾. Reduction in NOx emission might also be due to decrease of the residence time at high temperature by rapid mixing of the combustion products with the cold reactants⁽¹⁷⁾. A combination of the above effects may also contribute to reduce the level of NOx emission in the present study.

With $Q_{sec} = 4.2$ L/min, emission index shows higher values at $\phi = 0.70 \sim 0.75$ compared with $Q_{sec} = 3.0$ L/min, whereas it decreases in the range of $\phi = 0.80 \sim 0.85$. Figures 5 and 6 also illustrate the variation of pressure fluctuation and noise level versus the equivalence ratio for various amount of secondary fuel injection rate for nozzle type A. By adding secondary fuel injection of $Q_{sec} = 3.0$ or 4.2 L/min, a large amount of noise level reduction is observed in lower equivalence ratios which is accompanied by reduction in pressure oscillation level. As suggested in the previous study of Choi et al.⁽¹¹⁾, this noise level reduction might be ascribed to the elimination of pressure fluctuations through the control of local flame structure by injection of secondary fuel. In addition, as proposed by Tanahashi et al.⁽¹²⁾, the secondary fuel injection reduces the spatial and temporal fluctuations of the high temperature gas in the recirculation zone. This suppression corresponds to a decrease of the turbulent Reynolds number in the recirculation zone. As the number of fine scale eddies decreases, the Reynolds stress term and the entropy term associated with the turbulent energy dissipation are reduced in a viewpoint of the sound source, as stated in the study of Tanahashi et al.⁽²⁰⁾. This mechanism leads to the noise

reduction with consequential effects in the flame zone.

These results show that $Q_{\text{sec}} = 3.0$ L/min is the best condition for the reduction of pressure fluctuation and combustion noise with tolerable NOx emission for the injector A as shown in the previous studies^{(11),(19)}. It is also noteworthy that the noise level and pressure fluctuations of the injector A are decreased by increasing the amount of secondary fuel to 4.2 L/min in the range of $\phi \geq 0.85$. Therefore, this injector could be applicable for reduction of noise level and pressure oscillation with $Q_{\text{sec}} = 4.2$ L/min in near stoichiometric operating conditions.

Fig. 4 Variation of emission index by the amount of secondary fuel injection for the injector type A.

Fig. 5 Variation of r.m.s. of pressure fluctuations by the amount of secondary fuel injection for the injector type A.

Fig. 6 Variation of noise level by the amount of secondary fuel injection for the injector type A.

Fig. 7 Emission index for $Q_{\text{sec}} = 1.8$ L/min.

Fig. 8 R.m.s. of pressure fluctuations for $Q_{\text{sec}} = 1.8$ L/min.

Fig. 9 Noise level for $Q_{\text{sec}} = 1.8$ L/min.

The injector dependence of emission index, r.m.s. of pressure fluctuations and noise level as a function of equivalence ratio for $Q_{\text{sec}} = 1.8$ L/min are shown in Figs. 7-9. Emission index of all the injectors exhibit higher values than that of the no control condition for all equivalence ratios. For the injector B, NOx emission shows the same trend as injector A in lean operating condition ($\phi \leq 0.80$), whereas it reduces with increase of equivalence ratio ($\phi > 0.80$). As for the injectors C and D, emission index exhibits a similar trend and lower values than that of the injector A in the whole range of equivalence ratios. On the other hand, combustion noise level for all the injectors decreases by injecting secondary fuel. The structure of the flames, for the present experimental conditions is classified into the corrugated flamelets regime of the turbulent combustion diagram^{(12), (13), (18)}. The local

flame elements can be considered to be laminar flamelets in this regime, and the local heat release rate is approximated to be that of the laminar flame. As proposed in previous related studies⁽¹³⁾, the vortical structures enhance the entropy term of the acoustic sound source. Therefore, reduction of combustion noise for $Q_{\text{sec}} = 1.8$ L/min can be attributed to the suppression of large-scale vortical motion formed in the recirculation zones and the reduction of flame front fluctuation⁽¹³⁾.

Noise level of the injector B is lower than that of the other injectors for the whole range of equivalence ratios. Pressure fluctuation of injector B is lower than that of no control condition in $\phi \leq 0.80$ and increases for higher equivalence ratios. Pressure oscillation and noise level with the injector C show lower values than those of the injector D except for $\phi = 0.70$. These results show that the injector C might be more effective than the injector D for the reduction of pressure fluctuation and noise level with $Q_{\text{sec}} = 1.8$ L/min, and that the injector B, with higher injection velocity than those of the other injectors due to its smaller injection diameter, is the most relevant injector for reduction of noise level with $Q_{\text{sec}} = 1.8$ L/min with a tolerable NOx emission and pressure oscillation.

Fig. 10 Emission index for $Q_{\text{sec}} = 3.0$ L/min.

Figures 10-12 illustrate the variation of emission index, r.m.s. of pressure fluctuations and noise level for $Q_{\text{sec}} = 3.0$ L/min. For all the injectors, by increasing flow rate of secondary fuel from 1.8 L/min to 3.0 L/min, emission index shows higher values in $\phi = 0.70 \sim 0.75$, whereas it is decreased in $\phi > 0.80$. On the other hand, by increase of the secondary fuel to 3.0 L/min, the pressure fluctuation is reduced in $\phi = 0.70 \sim 0.75$, whereas it increases in $\phi \geq 0.85$. In addition, noise level tends to decrease for the whole range of equivalence ratios. The injector B shows a same trend for emission index with the injector A except for $\phi = 0.8$, whereas pressure fluctuation and combustion noise for this injector increase from lower equivalence ratio ($\phi = 0.75$) compared with those of the injector A. For the injector C, pressure fluctuation increases for the whole range of equivalence ratios compared with the injector A and B. Furthermore, for $\phi > 0.8$, the injector C induces pressure fluctuation higher than that of no control condition. However, the emission index of the injector C is lower than those of the injector A and B for the whole range of equivalence ratios. For the combustion noise, although the injector C is worse than other injectors, the noise level is still lower than those of no control case. As for the injector D, the emission index exhibits the same trend with the injector C, whereas pressure fluctuation and noise level show lower value in $\phi < 0.80$ and higher value in $\phi > 0.85$ compared with the injector C. These results suggest that the injector C might be more applicable than the injector D for the reduction of NOx, with $Q_{\text{sec}} = 3.0$ L/min, in near stoichiometric operating condition. It is also worth to note that the injector A is considered to have a better performance than other injectors for the reduction of pressure fluctuation and noise level in $\phi < 0.80$.

Fig. 11 R.m.s. of pressure fluctuations for $Q_{\text{sec}} = 3.0$ L/min.

Fig. 12 Noise level for $Q_{\text{sec}} = 3.0$ L/min.

Fig. 13 Emission index for $Q_{\text{sec}} = 4.2$ L/min.

The variations of emission index, r.m.s. of pressure fluctuations and noise level are plotted against the equivalence ratio for $Q_{\text{sec}} = 4.2$ L/min in Figs. 13-15. Emission index for the injector B increases with increment of flow rate of secondary fuel from 3.0 to 4.2 L/min, and shows higher values compared with the injector A in the whole range of equivalence ratios except for $\phi = 0.85$. However, for high equivalence ratio ($\phi = 0.90$), pressure fluctuation is more suppressed than that of the injector A. For the injectors C and D with higher secondary fuel flow of 4.2 L/min at $\phi = 0.70 \sim 0.80$, emission index is increased compared with $Q_{\text{sec}} = 3.0$ L/min. However NOx emission decreases in $\phi \geq 0.85$. The similar trend of emission index with the injectors C and D indicates that NOx emission has no dependency on the direction of injection offset. In addition, for the injectors with injection

offset, emission index shows lower value than those of the injectors A and B for the whole range of equivalence ratios.

Fig. 14 R.m.s. of pressure fluctuations for $Q_{\text{sec}} = 4.2$ L/min.

Fig. 15 Noise level for $Q_{\text{sec}} = 4.2$ L/min.

From the viewpoint of flame shapes, the lifted flames which are generated by the injectors C and D emit lower NO_x than the flame of the injectors without injection offset. It is inferred from the results that the NO_x emission reduction by flame lift-off over the swirl nozzle, which has also been reported in a previous study⁽¹¹⁾, became more pronounced by secondary fuel injection with offset. In addition, pressure fluctuations and noise level are decreased by increasing the amount of secondary fuel from 3.0 L/min to 4.2 L/min in $\phi \geq 0.85$, whereas the injector C shows lower pressure fluctuation than that of the injector D. These results show that the injector C with larger amount of secondary fuel is more effective, than injector D, for the reduction in pressure fluctuation and noise level of the combustor, especially in $\phi \geq 0.85$. However, the levels of its pressure fluctuation and combustion noise are still higher than those for the injectors without injection offset in near stoichiometric operating condition. On the contrary, for lean operating conditions ($\phi < 0.80$), pressure fluctuation is reduced by increasing the amount of secondary fuel from 3.0 L/min to 4.2 L/min.

As mentioned by Shimura et al.⁽¹³⁾ regarding the present combustor, for no control case, large-scale vortical structures are generated in regions around the axial centerline of the combustor and outer edge of the swirl nozzle. These large-scale vortical motions induce fluctuation of flame front, i.e., fluctuation of heat release rate, and enhance the entropy term in acoustic sound source. Therefore, suppression of the large-scale vortical motion formed in the recirculation zones is important for the reduction of flame front fluctuation and combustion noise. They⁽¹³⁾ suggested that turbulent intensity in the inner recirculation zone

is higher than that in the outer recirculation zone. Therefore, injection of secondary fuel to inner recirculation zone is more effective to suppress combustion oscillation. They also observed that compared with no control case, the region of recirculation zone for the case of continuous injection with no offset (i.e., the reference injector) is expanded and magnitude of fluid velocity is decreased in region near the swirler exit. The secondary fuel injection with no offset suppresses the velocity fluctuation around the inner recirculation zone and that near the exit of swirl nozzle. These suppressions cause reduction of flame front fluctuation and fluctuation of heat release rate. Therefore, secondary fuel injection with no offset contributes to reduction of the entropy term in acoustic sound sources.

In the framework of the explanations proposed above, the higher level of pressure fluctuations and lift-off of the flames with injection offset can be attributed to the off-centered injection of secondary fuel into the inner recirculation zone. In other words, due to the inappropriate injection of the secondary fuel to the inner recirculation zone, with the high rate of 4.2 L/min in the case of injection with offset, large-scale vortical motion enhances rather than being suppressed inside the recirculation zone. This will intensify the effects of inner and outer large-scale vortical structures on the fluctuation of flame front. As a consequence of the enhanced large-scale vortical motion, the entropy terms in the acoustic sound source increase and the combustion noise will enhance relative to the case of flames without injection offset. In addition, this injection of the secondary fuel with offset to the inner recirculation zone would also influence on the level of fuel-air mixing. Reduction in degree of fuel-air mixing⁽¹⁵⁾ together with some other complementary mechanisms such as reduced residence time at high temperature, by rapid mixing of the combustion products with the cold reactants⁽¹⁷⁾, are responsible for the lower NO_x formation found in the case of flames with injection offset.

5.1 Spectral Analysis of Pressure Fluctuations

The cases of $\phi = 0.70$ and 0.90, which are representatives of lean and near stoichiometric conditions, are focused in the following sections. Figure 16 shows the power spectra of pressure fluctuations for $\phi = 0.70$ without secondary fuel and with secondary fuel injection (injector type A) of $Q_{\text{sec}} = 0.6 \sim 4.2$ L/min. For no control condition, an instability mode can be observed around 140 Hz. Low secondary fuel injection rate of 0.6 L/min is not effective for suppression of pressure fluctuation. Moreover, additional peaks are generated in frequency range higher than the dominant mode. By increasing the flow rate of secondary fuel to 1.8 L/min, energy at the dominant frequency is reduced, and therefore combustion noise level and pressure oscillation are decreased as shown in Figs. 5 and 6. However, new modes are induced at about 125, 100 and 80 Hz. These new modes can be suppressed by the increase of secondary fuel more than 3.0 L/min. The power spectra for the injectors B, C and D show the similar tendency for lower equivalence ratio (not shown here).

Power spectra of pressure fluctuations with injector A for $\phi = 0.90$ is illustrated in Fig. 17. For no control condition, an instability mode can be observed at about 180 Hz. With low amount of secondary fuel (0.6 L/min), pressure fluctuation is not suppressed and new instability modes are not induced in contrast to the case of $\phi = 0.70$. For $Q_{\text{sec}} = 1.8$ L/min, although the energy at the dominant frequency of 180 Hz is decreased compared with that of no control condition, a new dominant peak is generated at lower frequency of about 160 Hz. With the increase of secondary fuel to 3.0 L/min, the dominant peak shifts to the lower frequency of about 145 Hz, and two peaks at 145 Hz and 180 Hz become apparent. For $Q_{\text{sec}} = 4.2$ L/min, three peaks at about 160 Hz (dominant), 145 Hz and 180 Hz are induced. Whereas r.m.s. values of pressure fluctuations for $Q_{\text{sec}} = 1.8$ and 3.0 L/min is larger than that for no control condition, energy at each dominant mode is reduced with the increase of secondary fuel.

Fig. 16 Power spectra of pressure fluctuations for $\phi = 0.70$ (type A, $Q_{\text{sec}} = 0.0 \sim 4.2$ L/min).

Fig. 17 Power spectra of pressure fluctuations for $\phi = 0.90$ (type A, $Q_{\text{sec}} = 0.0 \sim 4.2$ L/min).

Fig. 18 Power spectra of pressure fluctuations for $\phi = 0.90$ (type B, $Q_{\text{sec}} = 0.0 \sim 4.2$ L/min).

Power spectra of pressure fluctuations with injector B for $\phi = 0.90$ is shown in Fig. 18. With secondary fuel flow of $Q_{\text{sec}} = 0.6$ L/min, pressure fluctuation increases but new instability modes are not induced. By increasing the secondary fuel flow to 1.8 L/min, although the energy at the dominant frequency of 180 Hz is decreased compared with that of no control condition, a new dominant peak is generated at lower frequency of about 160 Hz. With $Q_{\text{sec}} = 3.0$ L/min, the energy at the lower dominant mode of 160 Hz is decreased, whereas that of the 180 Hz is enhanced. In contrast to the $Q_{\text{sec}} = 3.0$ L/min, for 4.2 L/min, the energy at the dominant frequency of 180 Hz is decreased and the energy at the lower dominant mode of 160 Hz is enhanced again. In contrast to the injector A, by increase of the

secondary fuel to 4.2 L/min with injector B, new instability modes are not induced and the dominant modes appear in a narrower range of frequency compared with those of the reference injector.

Fig. 19 Power spectra of pressure fluctuations for $\phi = 0.90$ (type C, $Q_{\text{sec}} = 0.0 \sim 4.2$ L/min).

Fig. 20 Power spectra of pressure fluctuations for $\phi = 0.90$ (type D, $Q_{\text{sec}} = 0.0 \sim 4.2$ L/min).

Figure 19 shows power spectra of pressure fluctuations for the injector C at high equivalence ratio ($\phi = 0.90$). By increasing the amount of secondary fuel, the new peaks are generated and the dominant mode shifts toward lower frequencies (160 Hz, 125 Hz and 100 Hz for $Q_{\text{sec}} = 1.8$, 3.0 and 4.2 L/min respectively). Furthermore, it can be observed that energy at the dominant frequency is enhanced for $Q_{\text{sec}} = 3.0$ L/min. Although energy at the dominant frequency of 100 Hz is reduced by the large amount of secondary fuel of 4.2 L/min, many peaks appear in the broad range of frequency compared with the injector A. Since the practical combustors have a lot of resonance modes, this appearance of peak frequencies might be dangerous to induce the unexpected instability modes.

Figure 20 plots the power spectra of pressure fluctuations with the injector D for $\phi = 0.90$. By increasing the amount of secondary fuel new peaks are generated and the dominant mode shifts toward lower frequencies with a similar trend as the injector C. However, in contrast to the injector C, the pressure oscillation and the energy at the dominant frequency of 160 Hz is higher for $Q_{\text{sec}} = 1.8$ L/min. By secondary fuel of 4.2 L/min, the energy at another dominant frequency of 125 Hz is enhanced. Here also many peaks appear in the broad range of frequency compared with the reference injector.

To study the relation between the dominant mode of instability and NO_x emission the case of $\phi = 0.90$ with $Q_{\text{sec}} = 4.2$ L/min is considered. The combustion noise with all the injectors at $\phi = 0.90$ shows almost the same values with a maximum difference of less than 5 dB (see Fig. 15). Moreover, the injectors with the same induced mode of instability

exhibit almost a similar amount of emission index. However, NOx emission decreases with the injectors C and D which induce the dominant modes in a lower frequency range inside the combustor. Similar trends are also observed in other operating conditions for the injectors with the same amount of noise level. These results suggest that the emission index is deeply related to the dominant mode of instability.

6. Summary

The effects of secondary fuel injection rate, injection diameter and injection offset on combustor noise level, r.m.s. of pressure fluctuations and NOx emission level were studied in the turbulent swirl stabilized combustor. Four different types of secondary fuel injectors were used for an overall equivalence ratio range of $\phi = 0.7 \sim 0.9$.

Secondary fuel injection of $Q_{\text{sec}} = 3.0$ L/min is the best condition for the reduction of pressure fluctuation and combustion noise with tolerable NOx emission for the reference injector which has been confirmed by previous studies^{(11),(19)}. Reduction of the injection diameter, which provides a higher injection velocity than that of the reference injector, allow the lower secondary fuel rate of 1.8 L/min to decrease the noise level and pressure fluctuation with a tolerable NOx emission. This can be due to the proper penetration of the secondary fuel into the inner recirculation zone because of the higher momentum of fuel afforded by the reduction of injection diameter in this condition. As a consequence, secondary fuel injection, in this condition, will suppress the velocity fluctuation and large-scale vortical motion in the inner recirculation zone⁽¹³⁾. By these suppressions, the flame front fluctuation and fluctuation of heat release rate will reduce. This will lead to reduction of the entropy term in acoustic sound source and decreases the combustion noise.

Secondary fuel injection with offset leads to the reduction of NOx emission for the whole range of equivalence ratios compared with those of the injection without offset. Low emission index by flame lifting off from the swirl injector which was also reported in another related study⁽¹¹⁾, is more pronounced with injection offset by increase of the secondary fuel rate to 4.2 L/min in near stoichiometric operating condition ($\phi \geq 0.85$). On the other hand, pressure fluctuation enhances for the injectors with injection offset. The fluctuating behavior and lift-off of the flames with injection offset can be ascribed to the off-centered injection of secondary fuel into the inner recirculation zone which will cause to enhance the large-scale vortical motion and would intensify the effects of inner and outer large-scale vortical structures on the fluctuation of flame front. This enhances entropy terms in the acoustic sound source and increases the combustion noise relative to the case of flames without injection offset. This secondary fuel injection with offset will also contribute to the reduction in degree of fuel-air mixing and a reduced residence time at high temperature which would be responsible for the lower amount of NOx in the case of flames with injection offset. The undesirable increase in combustion noise and fluctuating behavior of the flame for the case of injection with offset indicates the flame structure sensitivity to trajectory of the secondary fuel.

Spectral analysis of pressure fluctuations revealed that larger amount of secondary fuel by the injectors with injection offset induce a lot of new modes in the wide range of frequency. In addition, these instability modes with injection offset appear in frequency ranges that are lower than those of the injection without offset.

The results obtained in this study suggested that the emission index and the dominant mode of instability are deeply related to flame shapes and local flame structure. The mechanism of the broadening of peak frequencies will be investigated by laser diagnostics, such as simultaneous measurement of CH-OH planar laser induced fluorescence and stereoscopic particle image velocimetry⁽¹⁸⁾ or 3D reconstruction of flame structure⁽¹²⁾.

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References

- (1) Zimont, V. L., Theory of Turbulent Combustion of a Homogeneous Fuel Mixture at High Reynolds Numbers, *Combustion, Explosion, and Shock Waves*, Vol. 15 (1979), pp. 305–311.
- (2) Chaparro, A., Landry, E. and Cetegen, B. M., Transfer Function Characteristics of Bluff-Body Stabilized, Conical V-Shaped Premixed Turbulent Propane–Air Flames, *Combustion and Flame*, Vol. 145, (2006), pp. 290–299.
- (3) Broda, J. C., Seo, S., Santoro, R. J., Shirhattikar, G. and Yang, V., An Experimental Study of Combustion Dynamics of a Premixed Swirl Injector, *Proceedings of the Combustion Institute*, Vol. 27 (1998), pp. 1849–1856.
- (4) Candel, S., Combustion Dynamics and Control: Progress and Challenges, *Proceedings of the Combustion Institute*, Vol. 29 (2002), pp. 1–28.
- (5) Dowling, A. P. and Stow, S. R., Acoustic Analysis of Gas Turbine Combustors, *Journal of Propulsion and Power*, Vol. 19, No. 5 (2003), pp. 751–764.
- (6) Ducruix, S., Schuller, T., Durox, D. and Candel, S., Combustion Dynamics and Instabilities: Elementary Coupling and Driving Mechanisms, *Journal of Propulsion and Power*, Vol. 19, No. 5 (2003), pp. 722–734.
- (7) Bellows, B. D. and Lieuwen, T., Nonlinear Response of a Premixed Combustor to Forced Acoustic Oscillations, *AIAA-2004-0455*.
- (8) Rayleigh, L., The Theory of Sound, (1878 reedited in 1945) Dover, New York.
- (9) Lee, J. G., Kim, K. and Santavicca, D. A., Effect of Injection Location on the Effectiveness of an Active Control System Using Secondary Fuel Injection, *Proceedings of the Combustion Institute*, Vol. 28, No. 1 (2000), pp. 739–746.
- (10) Tachibana, S., Zimmer, L., Kurosawa, Y. and Suzuki, K., Active Control of Combustion Oscillations in a Lean Premixed Combustor by Secondary Fuel Injection Coupling with Chemiluminescence Imaging Technique, *Proceedings of the Combustion Institute*, Vol. 31 (2007), pp. 3225–3233.
- (11) Choi, G.-M., Tanahashi, M. and Miyauchi, T., Control of Oscillating Combustion and Noise Based on Local Flame Structure, *Proceedings of the Combustion Institute*, Vol. 30, No. 2 (2005), pp. 1807–1814.
- (12) Tanahashi, M., Inoue, S., Shimura, M., Taka, S., Choi, G.-M. and Miyauchi, T., Reconstructed 3D Flame Structures in Noise-Controlled Swirl-Stabilized Combustor, *Experiments in Fluids*, Vol. 45, No. 3 (2008), pp. 447–460.
- (13) Shimura, M., Tanahashi, M., Choi, G.-M. and Miyauchi, T., Large-Scale Vortical Motion and Pressure Fluctuation in Noise-Controlled Swirl-Stabilized Combustor, *Journal of Thermal Science and Technology*, Vol. 4, No. 4 (2009), pp. 494–506.
- (14) De Zilwa, S. R. N., Sivasegram, S. and Whitelaw, J. H., Control of Combustion Oscillations Close to Stoichiometry, *Flow, Turbulence and Combustion*, Vol. 63, (1999), pp. 395–414.
- (15) Ballester, J., Sanz, A. and Gonzalez M. A., Investigation of the Characteristics and Stability of Air-Staged Flames, *Experimental Thermal and Fluid Science*, Vol. 32, (2008), pp. 776–790.
- (16) Poppe, C., Sivasegaram, S. and Whitelaw, J. H., Control of NO_x Emissions in Confined Flames by Oscillations, *Combustion and Flame*, Vol. 113 (1998), pp. 13–26.
- (17) Keller, J. O. and Hongo, I., Pulse Combustion: The Mechanisms of NO_x Production, *Combustion and Flame*, Vol. 80, (1990), pp. 219–237.
- (18) Tanahashi, M., Murakami, S., Choi, G.-M., Fukuchi, Y. and Miyauchi, T., Simultaneous CH-OH PLIF and Stereoscopic PIV Measurements of Turbulent Premixed Flames, *Proceedings of the Combustion Institute*, Vol. 30 (2005), pp. 1665–1672.
- (19) Tanahashi, M., Murakami, S., Miyauchi, T. and Choi, G.-M., Control of Oscillating

- Combustion and Measurements of Turbulent Flames, *Proceedings of 5th Symposium on Smart Control of Turbulence*, (2004), pp. 75–84.
- (20) Tanahashi, M., Tsukinari, S., Saitoh, T., Miyauchi, T., Choi, G.-M., Ikame, M., Kishi, T., Harumi, K. and Hiraoka, K., On the Sound Generation and its Controls in Turbulent Combustion Field, *Proceedings of 3rd Symposium on Smart Control of Turbulence*, (2002), pp. 149–160.