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Combustion Control by Additional Fluid Injection for Premixed Gas Turbine Combustor

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Abstract:

This paper deals with the effect of secondary fluid injection on oscillatory combustion of a turbulent premixed flame. The effect of injection angle and fluid type on pressure fluctuations and NOx emissions was investigated. Characteristics of pressure fluctuations, NOx emissions and flame shapes (OH* chemiluminesence image and OH-PLIF measurement) were discussed. The results indicated that air-injection inclined at 45 degrees from streamwise direction was effective to stabilize the oscillatory flame. However, NOx emissions were slightly increased. Furthermore, it was found that secondary injection inclined at 90 degrees showed good performance to reduce NOx emissions successfully.

Key Words:

Premixed Flame, Oscillatory Combustion, Combustion Control, Secondary Injection

1. INTRODUCTION

Gas turbine engines have traditionally used diffusion flame combustors because they provide reliable performance and reasonable stability characteristics. However, this type of combustor produces high amount of thermal NOx emissions. In order to reduce pollutant emissions and increase the combustion load, the lean premixed combustion (LPC) has been used as an effective technique. Although LPC has an advantage to reduce NOx emission, unsteady flow oscillations referred to as combustion instability or dynamics have often emerged. In the flow field with large amplitude of the pressure oscillations, structural vibration of the equipment will be induced and the system fails into disrepair.

Aerodynamic oscillations in the combustor are typically classified into Helmholtz type or longitudinal acoustic oscillation. When the fluctuation of heat release rate is combined with one of the acoustic oscillation modes in the combustor, self-excited oscillatory combustion is induced. The oscillatory combustion may caused by the interaction among the effects of acoustics, heat release and aerodynamic such as vortex (Sato, *et al.* 2007). Schematic of the interaction is shown in Fig. 1. It is well known that the coupling between pressure and heat release fluctuations will add energy to the instabilities, and the condition is called as Rayleigh's criterion (Rayleigh 1945). Generally, the pressure and heat release rate fluctuations have a phase difference. When the phase difference (τ) is in the range of $-\pi/2 < \tau < \pi/2$, the Rayleigh's criterion representing the onset of self-excited oscillation is satisfied.

In order to control the self-excited combustion oscillation, we can make a choice between passive control and active control. For example, the former is achieved by changing the geometry of combustors, and the latter is completed by modifying the feed rate defined by the rate of fuel and oxidizer (e.g., Katsuki and Whitelaw 1986, Candel 2002). Combustion oscillations can be considered as a

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resultant phenomenon of strong coupling between the fluctuations of pressure and heat release rate. In order to avoid unsteady combustion, development of combustion control techniques has been a focus of attention recently. Passive control strategies are implemented with providing an acoustic damping (*e.g.,* Huzel and Huang 1992, Sivasegaram, *et al.* 1995, Blonbou, *et al.* 2000). However this approach is usually not successful at eliminating all instabilities, and furthermore, there is less degrees of freedom for designing the combustors. Therefore, active combustion control (ACC) techniques are necessary for an effective and robust combustion control.

To obtain important factors for combustion instabilities control, several studies have been conducted for flame-acoustic interactions using phase-locked measurements (*e.g.,* Samaniego, *et al.* 1993, Broda, *et al.* 1998). Investigations on NOx reduction by using passive or active control have also been conducted (*e.g.,* Poppe, et al. 1998, Murugappan, *et al.* 2000). Since the heat release rate plays important role in the sound generation mechanism, it is very informative to identify the dominant sound source with understanding spatial and temporal fluctuations of the heat release rate of the combustor (Tanahashi, et al. 2002). To reduce NOx emissions, the combustor is operated under much more fuel lean conditions. However, there are some problems to use lean combustion such as oscillatory flame, blow-off and so on.

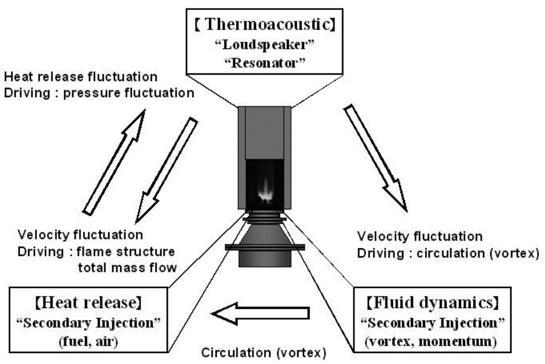


Fig. 1. Schematic image of dominant factors on oscillatory combustion

In this study, effects of additional fluid injections on the oscillatory combustion of turbulent premixed flame are discussed as an active combustion control technique. Experiments are performed in a swirl-stabilized combustor with inner secondary injection holes. Phase-locked OH-PLIF (planar laser induced fluorescence) measurement is also conducted to understand chemical reaction with flame fluctuations.

2. EXPERIMENTAL APPARATUS

The schematic diagram of the experimental setup is shown in Fig. 2. Experiments are performed using a swirl-stabilized combustor in which a dominant oscillatory mode will correspond to the 1/4 wavelength mode of thermoacoustics in the combustor. Size of the combustion rig is 100mm × 100mm as the inner cross-section. The total length of the combustion chamber is 550mm. Swirl nozzle with inclined vanes of 30 degrees was used as a flame holder. The swirl injector has 10mm inner diameter and 30mm outer diameter, and there are 12 injection holes (dia.=1.0mm) which are inclined 45 or 90 degrees from streamwise direction. These inner injections were used as an additional fluid injection to control oscillatory flame. Methane and pre-heated air (700K) were used as fuel and oxidizer, respectively.

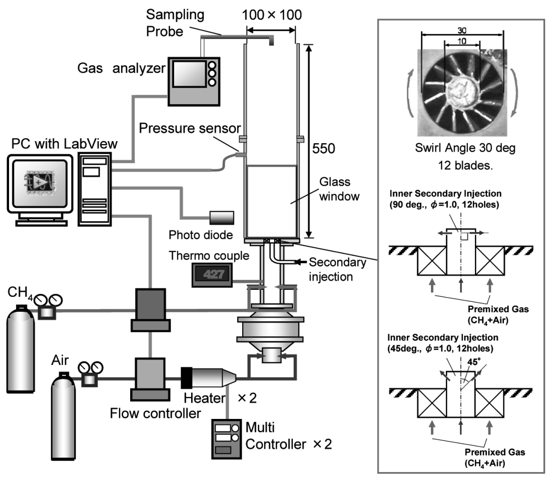


Fig. 2. Experimental setup

Working fluid as the secondary injection was methane or air.

The pressure transducer (Kistler, 4045A5) was used to measure pressure fluctuations in the combustion chamber. OH* chemiluminesence was detected by a photo-sensor (HAMAMATSU Photonics Co., S2281) with a band-pass (310nm ± 10) optical filter (Asahi Optics Co., MX03) as an index of heat release fluctuations. The concentration of nitric oxides was measured by a combustion gas analyzer (Horiba Co., PG-240).

On each side of the combustion chamber, a silica glass plate is installed to allow optical access. Figure 3 shows OH-PLIF measurement system. The fluorescence form OH radicals in the flame was produced with an Nd-YAG laser (Spectra-Physics, PIV400-10). This was used to pump the OH $A^2\Sigma \leftarrow A^2\Pi$ electronic transition to 283.6nm using a dye laser (Lamda Physics, Scanmate UV) with SHG units. Image of the fluorescence and chemiluminesence form OH radicals was taken by an image intensified CCD camera (LaVision, NanoStar) with a UV-Nikkor 105mm / f4.5 lens. Laser and camera system was controlled with a PC based control software, and phase locked measurements were conducted for OH-PLIF and OH* chemiluminesence.

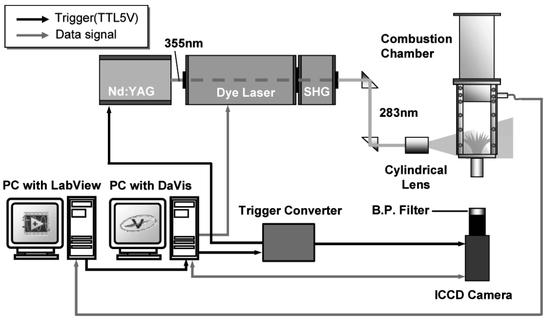


Fig. 3. PLIF system

3. RESULTS AND DISCUSSION

3.1 Combustion Chalacteristics

In order to clarify combustion chalacteristics of the combustor, pressure fluctuations and NOx emissions were measured as a function of equivalence ratio, ϕ. And furthermore, a normalized function of cross-correlation, $C_{p'q'}$, which is based on the r.m.s. signals from pressure transducer and photo sensor was indicated to determin Rayleigh's criterion. Value of cross-correlation between pressure fluctuations and heat release fluctuations was calculated from the following formula

$$C_{p'q'}(t) = \frac{\lim_{T\to 0}\frac{1}{T}\int_{-T/2}^{T/2} p(t)q(t-\tau)dt}{\sqrt{R_{p'p'}(0)}\sqrt{R_{q'q'}(0)}} \tag{1}$$

From this function, similarities of the signals and time-delay are discussed.

Figure 4 shows pressure fluctuations and normalized corss-correlation. Result of NOx emissions is also indicated in Fig. 5. The flow rate of main mixture fuel was held on 16 l/min, and equivalence ratio was varied from lean blow-off limit to ϕ=1.0, respectively. From the result of Fig. 4, the values of pressure fluctuations and normalized cross-correlation show significantly large level between ϕ=0.6 and 1.0. Particulary, pressure fluctuations are intensified at the range from ϕ=0.8 and 0.9. In Fig. 5, the value of NOx emissions is gradually decreased according to the condition of lean burnig. This tendency corresponds to the flame temperature; the temperature turns down with a decrease in equivalence ratio. As a result, NOx emissions are suppressued due to the reduction of thermal NO.

In this study, the object is to control oscillatory combustion. So the condition of oscillatory flame (experimental condition) was definitiezed with ϕ=0.85, in which pressure fluctuations were very strong ($p'_{r.m.s.}$=1.69kPa). Properties of the flame indicate with Table 1, and Figure 6 shows time-series data of pressure fluctuations and their power spectrum. In Fig. 6, Q_f is mass flow rate of fuel and Q_a indicates air flow rate. In this oscillatory flame, a dominant frequency is 202Hz which correspnds to excitation of a quarter-wave mode of the combustion chamber, when the mean temperature of the chamber inside is assumed to be 1000-1300K.

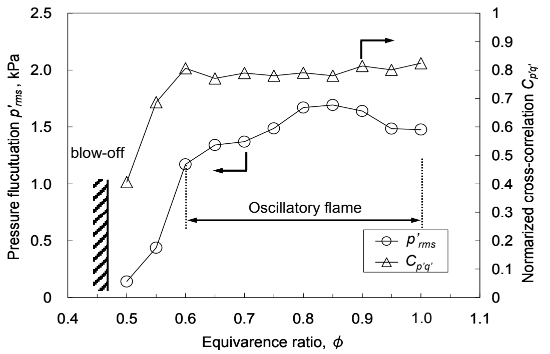


Fig. 4. Effect of equivalence ratio on pressure fluctuations and normalized cross-correlation

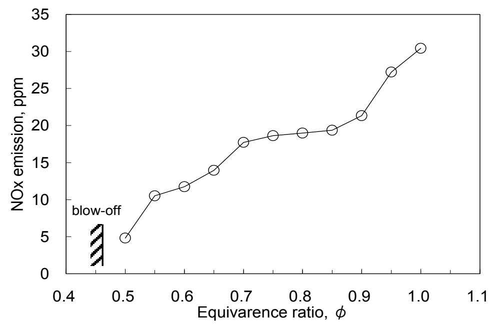


Fig. 5. Effect of equivalence ratio on NOx emissions

Table I. Combustion property（ϕ=0.85）

Pressure fluctuation , p'_{rms}	1.69 [kPa]
Frequency, f	202 [Hz]
Normalized cross-correlation, $C_{p'q'}$	0.78 [-]
NOx emission	20.3 [ppm]

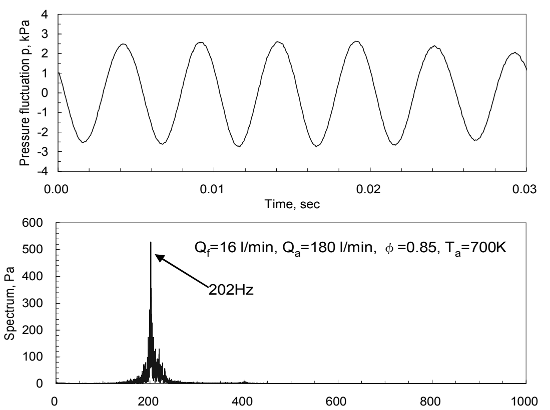


Fig. 6. Measured S-parameters and phase difference

From the result of power spectrum, we can observe a simple mode without other oscillatory modes. As for the value of NOx emissions, time-averaged measurement was adopted. In this condition, the value was 20.3ppm. And the value of $C_{p'q'}$ indicated 0.78.

Figure 7 shows phase-locked OH* chemiluminesence images of the self-excited oscilaltion. Flame conditions are fuel flow rate Q_f = 16 l/min, air flow rate Q_a=180 l/min, equivalence ratio ϕ=0.85, inlet air temperature T_a=700K. Each of pictures is accumulated data of 100 images. Flame shape was varied with pressure fluctuations. Particularly, we can observe violent deformation of the flame with strong pressure fluctuations (i.e., $0 < f < \pi / 2$). From the result of OH* chemiluminesence images, it seems that behavior of the flame correlates with hydrodimanic motion of the vortex.

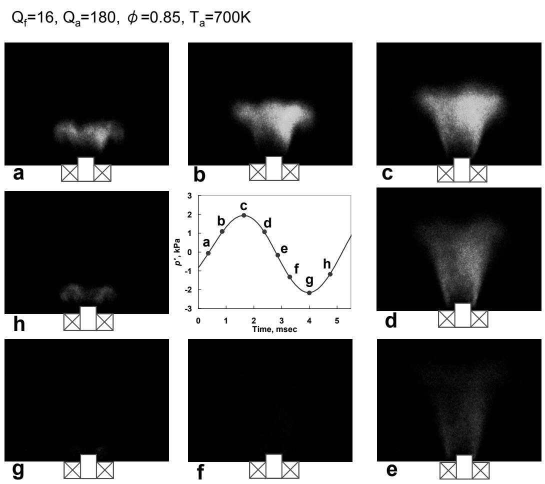


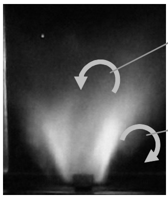
Fig. 7. Phase-locked OH* chemiluminescence images of the self-excited oscillation (average of 100 images)

3.2 Image Analysis

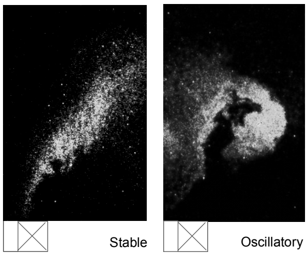
In order to determine the concept of active combustion control (ACC) using additional fluid injections, image analysis was carried out with OH-PLIF measurement. Figure 8 shows the direct photograph of the oscillatory flame and OH-PLIF images for stable and unstable flames. The image of OH-PLIF was taken with one shot of the laser light.

In Fig. 8(a), inner recirculation zone (IRZ) and corner recirculation zone (CRZ) are defined. Since the combustor has a swirl flame holder and abrupt expansion section, the recirculation zone was formed in the center and the outside of flow field.

In Fig. 8(b), we can compare the oscillatory flame with the stable flame. Oscillated flame undergoes deformation in CRZ due to the formation of vortex. Furthermore, we can presume that heat release fluctuation is intensive in the share layer between swirl and recirculation flow. Hence, as the concept of ACC using additional fluid injections, it is important to interrupt the feedback-loop between pressure and heat release fluctuations by using inner and outer injections to disturb the heat release fluctuation in the share flow zone (IRZ) and the flow field in CRZ, respectively.



(a) Direct photograph of oscillatory flame



(b) OH-PLIF images

Fig. 8. Flame characteristics: (a) direct photograph of the oscillatory flame, (b) OH-PLIF images

3.3 Effect of Secondary Injection under Constant Equivalence Ratio

According to the results of image analysis, alteration of heat release fluctuations might turn to energy relaxation of the interaction between pressure and heat release oscillations. One of the effective method to control combustion instabilities actively is to use secondary injection. In this study, secondary fuel injection (SFI) and secondary air injection (SAI) were attempted. Overall equivalence ratio condition was kept by dividing amount of fuel, which means that one line is provided as main flow injected from swirl injector and the other is as secondary flow supplied from inner injection holes. Distribution ratio (D.R.) of fuel is defined as

$$D.R.(fuel) = \frac{Q_{sf}}{Q_{mf} + Q_{sf}} \tag{2}$$

where Q_{mf} and Q_{sf} indicates flow rate of main fuel and that of secondary, respectively.

Figure 9 indicates the effect of SFI on pressure oscillations and NOx emissions. Flame conditions are fuel flow rate $Q_f = 16\,l$/min, air flow rate $Q_a = 180\,l$/min, equivalence ratio $\phi = 0.85$, inlet air temperature T_a=700K without secondary inejction. In the figure, a paramater described by Eq. (2) is represented. Furthermore, conditions of different injection angle (α=45 or 90 degrees) are also indicated. In the case of 45 degrees inclined injections, pressure oscillations are almost no variation, which means oscillatory flame is maintained. NOx emissions also indicate constant values for increasing secondary fuel injections. For 90 degrees inclined injections, pressure oscillations are slightly increased ($\Delta p'$=0.5kPa)

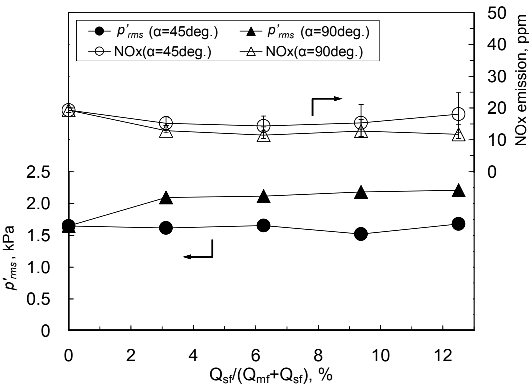


Fig. 9. Effect of SFI on p'_{rms} and NOx emissions

with an increase in secondary fuel injections. As for the result of NOx emissions, about 20% decrease is achieved by comparing with normal condition (*i.e.,* 0% secondary fuel injections). Correlation between pressure oscillations and NOx emissions is summarized as follows; when pressure fluctuations are amplified, NOx emissions are suppressed.

Using a different method of secondary injections, Whitelaw et al. reported that NOx emissions were suppressed with an increase in pressure fluctuations (Poppe, *et al.* 1998). The reason why NOx emissions are suppressed is due to amplified variation of flame shape. When the flame is fluctuated with an intensity, flame temperature (*i.e.,* chemical reaction) is suppressed because of the fluid interaction (*i.e.,* gas mixing) in combustion chamber. As the result, thermal NO is suppressed by reduced the flame temperature. Because thermal NO depends on flame temperature, in suppressing pressure fluctuations, NOx emissions are adversly increased.

Effect of secondary air injection (SAI) on oscillatory combustion is clarified with a view to providing hydrodynamic disturbance (*i.e.,* momentum effect). Distribution ratio of air is defined as

$$D.R.(air) = \frac{Q_{sa}}{Q_{ma} + Q_{sa}} \tag{3}$$

where Qma and Qsa indicates flow rate of main air and that of secondary, respectively.

Figure 10 shows the effect of SAI on pressure oscillations and NOx emissions. Flame conditions are fuel flow rate Q_f=16 *l*/min, air flow rate Q_a=180 *l*/min, equivalence ratio ϕ=0.85, inlet air temperature T_a=700K without secondary inejction. In the case of Fig. 9, overall equivalence ratio is maintained. In the case of 90 degrees inclined injections, magnitude of pressure oscillations is almost constant value when distribution ratio of air injections is increased. However, for 45 degrees inclined injections, pressure oscillations are suppressed with an increase in secondary air injections. Particularly, pressure oscillations are suppessed with about 7dB when the value of secondary air injections is 22.2% .

As for the result of NOx emissions, in the case of 45 degrees inclined injections, we can obtain the result of 15ppm increase at the most. In the case of 90 degrees inclined injections, effective result of NOx emissions shows a decrease of about 30% compared with normal condition, which is achieved under the condition of 12.2% distribution ratio of secondary air injections. As same as previous discussion, there is a tradeoff-correlation between pressure oscillations and NOx emissions. When the effect of pressure oscillations suppression is taken precedence, 45 degrees inclined injections as secondary air flow is more effective. On the other hand, for the effect of NOx emissions suppression, 90 degrees inclined air injections has good performance.

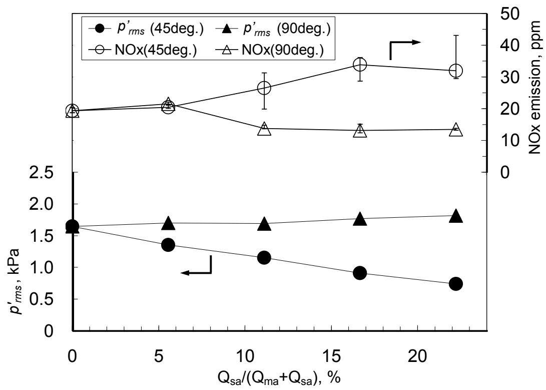


Fig. 10. Effect of SAI on p'_{rms} and NOx emissions

Images of OH-PLIF are shown in Fig. 11. Figures 11A and 11B is the result of SAI for 45 degrees and 90 degrees inclined injections, respectively. Result of SAI with 45 degrees inclined injections indicates that fluctuations of flame shape is no so strong and chemical reaction in space seems to be mild, which meanseffective control to suppress oscillatory combustion. In that case, we can see that interaction of pressure-heat release fluctuations are reduced in local distribution. On the other hand, the fluctuations are still maintained and chemical reaction becomes strong in the case of 90 degrees inclined injections.

That means ineffective control.

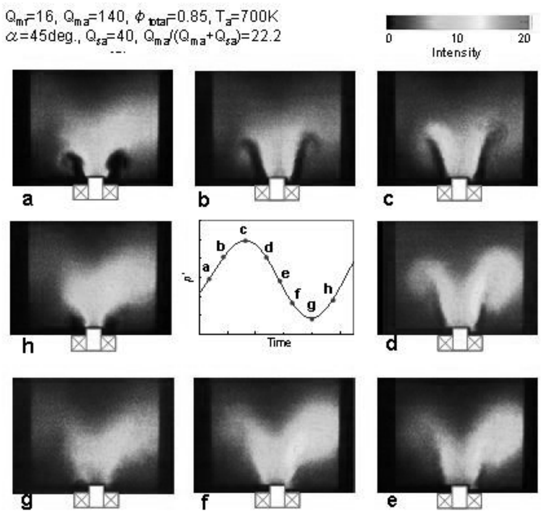


Fig. 11. 11A OH-PLIF imgaes for effective case ($\alpha=45$deg., $Q_{sa}/Q_{ma}+Q_{sa}=22.2$%)

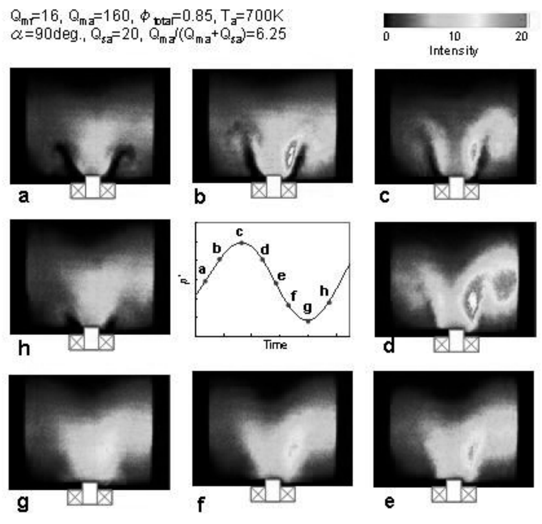


Fig. 11. 11B OH-PLIF images for non-effective case ($\alpha=90$deg., $Q_{sa}/Q_{ma}+Q_{sa}=6.25$%)

3.4 Seconday Air Injections involving Variation of Equivalence Ratio

From the results of secondary injections under the conditions of a constant overall equivalence ratio, we could obtain that the secondary air injections were effective to suppress pressure oscillations and NOx emissions. In order to reduce NOx emissions, lean burnig technology is one of the effective methods; so the secondary air injections involving the variation of overall equivalence ratio were conducted. Figures 12 and 13 shows the results of pressure oscillations and NOx emissions, respectively. In figures, we can observe the effect of lean burning on suppression of pressure fluctuations and NOx emissions compared with non-secondary injections. In the figures, fuel mass flow rate was constant to $Q_f=16\,l$/min, and air flow rate was $Q_a=180\,l$/min, where the equivalence ratio was $\phi=0.85$. According as the increased air injection for the secondary (second x-axis in the figure), condition of the overall equivalence ratio becomes lean burning.

Under the conditions of 90 degrees inclined injections, we can see that values of pressure fluctuations are almost the same at each equivalence ratio conditions compared with non-secondary injections. NOx emissions are gradually suppressed with an increase in amount of the secondary air injections. In the cases of 45 degrees inclined injections, drastic transformation of pressure oscillations is observed. Especially suppression effect of pressure fluctuations is about 20dB with sound pressure equivalent at the most lean burning condition (about $\phi=0.69$).

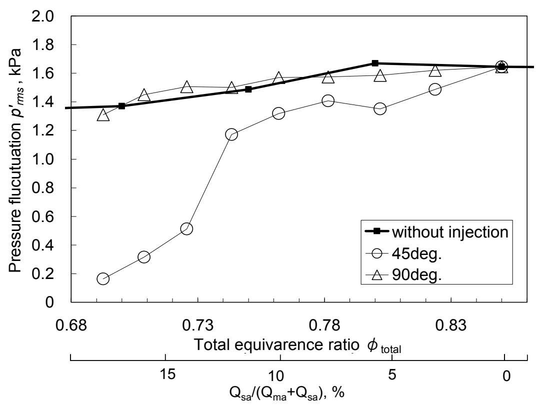


Fig. 12. Effect of SAI on pressure fluctuations

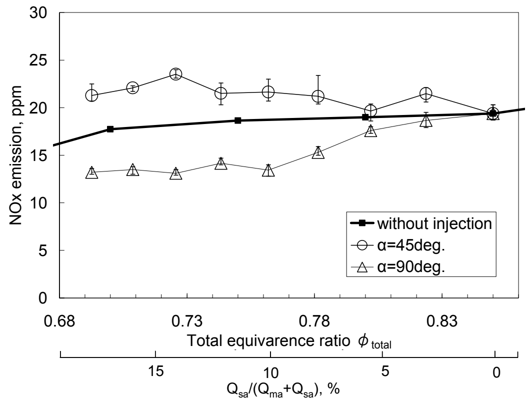


Fig. 13. Effect of SAI on NOx emissions

As for the results of NOx emissions, we can observe a tendency of slightly increase (about 5ppm). Compared to the same condition of the secondary air ainjection (*D.R.*=18.2%) with constant overall equivalence ratio (see. Fig. 10), increase of NOx emissions has been a large concentration under control up to about an 25% increase. Furthermore, in the same conditions (*D.R.*=18.2%), we could not observe any instabilities like a blow-off phenomenon while the secondary air injections were performed. Although week oscillations of pressure were observed, the flame was almost stable.

4. CONCLUDING REMARKS

In this investigation, an active combustion control using secondary injections was conducted. In order to clarify the driving source of oscillatory combustion, image analysis on OH-PLIF and OH* chemiluminesence was also investigated. As the result from image analysis, strong intensities of the reaction were shown at shear domain where the swirl flow interfered with rercerculation flow in the combustor. According to the result of OH-PLIF images, effects of secondary fuel injections and secondary air injections were investigated to suppress pressure oscillations and NOx emissions. As the result, additional air injections influenced to suppressing pressure oscillations and NOx emissions due to the momentum effect. Because there was a tradeoff-correlation between pressure oscillations and NOx emissions, when the effect of pressure oscillations suppression was taken precedence, 45 degrees inclined injections as secondary air flow was more effective. On the other hand, for suppressing NOx emissions, 90 degrees inclined air injections had good performance.

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