Combustion Instability in a Swirl Type Combustor

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Unstable combustion phenomena in a swirl type combustor were measured. OH chemiluminous intensity distributions were measured by using an ICCD camera with optical filters. Velocity distributions were measured by using a Particle Image Velocimetry (PIV) system. The results offer several guidelines for designing the lean premixed combustor. A new type combustor is designed and manufactured for demonstration.

1. Introduction

Lean premixed combustion is the most hopeful way for low NOx emission. However it is unstable near the lean limit. It is very important to understand the combustion instability and develop the control system. Therefore many studies have been conducted. Lieuwen et al. (1999, 2000) investigated combustion oscillations in a lean premixed gas turbine combustor theoretically and experimentally. De Zilwa et al. (2000) examined combustion oscillation of methane-air flames stabilized on a sudden-expansion in terms of the pressure and chemiluminescence of the CH radical. Steele et al. investigated passive combustion instability control in industrial combustor experimentally and numerically. Neumeier et al. (1996) and Pandalai et al. (1998) developed active control system, which used secondary fuel injections. Paschereit et al. (1999) controlled the instability with fuel injection modulation.

The Working Group for Turbulent Combustion Control is aiming to develop a control system that makes lean limit of premixed methane combustion lower than present combustors. Passive and active control methods to attenuate these instabilities are being studied. Our sub-group is working on the experimental combustor model for the demonstration of the combustion control system that will be developed. This model is operated in mixture condition of high velocity and high temperature to simulate the conditions of a gas turbine combustor except pressure. If the model itself has a mechanism to drive the instability, its intensity becomes too high to be controlled. The model must have passive control techniques such as flame holding method and configuration. Figure 1 shows the main relationship between demonstrator and other techniques. Monitoring techniques and an additional fuel injection system for the active control are being developed using smaller test burners. They will be applied to the demonstration combustor. The control algorithm for the demonstrator is being developed integrating these sensors and actuators. Evaluation of the control techniques will be conducted both experimentally and numerically.

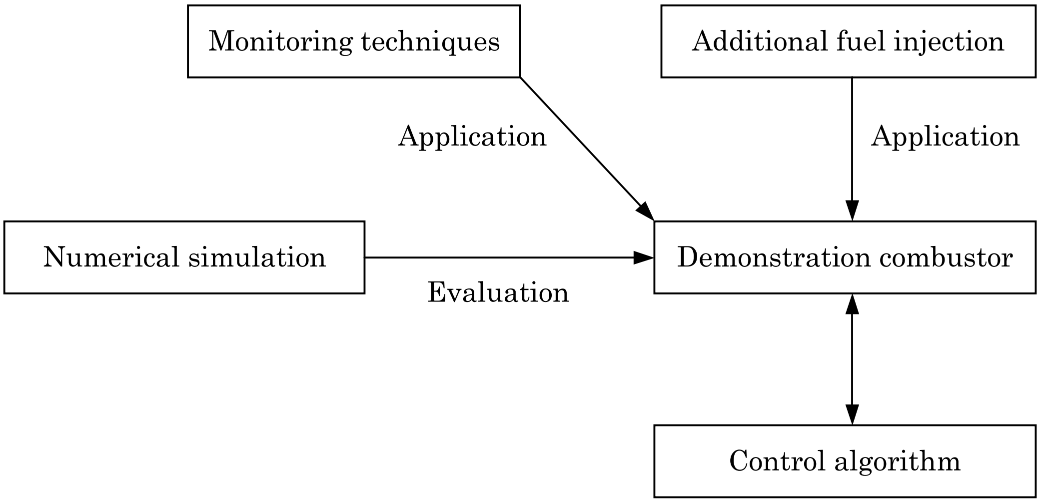


Fig. 1 Relationship between demonstrator and other techniques

Numerical simulation will also help to understand the phenomena observed in the experiments from an engineering point of view.

As mentioned above, the demonstrator must have good characteristics that are low lean limit, high combustion efficiency and stability without active controls. For designing the good combustor model, the instabilities have to be understood. Measurements were conducted about unstable phenomena in a swirl type combustor that is a typical gas turbine combustor. OH chemiluminescence was observed using an ICCD camera with optical filters. The velocity distribution is measured by a PIV (Particle Image Velocimetry) system.

2. Combustor Model and Measurement Systems

2.1 Experimental Combustor Model

Figure 2 shows the experimental combustor model. This model can be used for

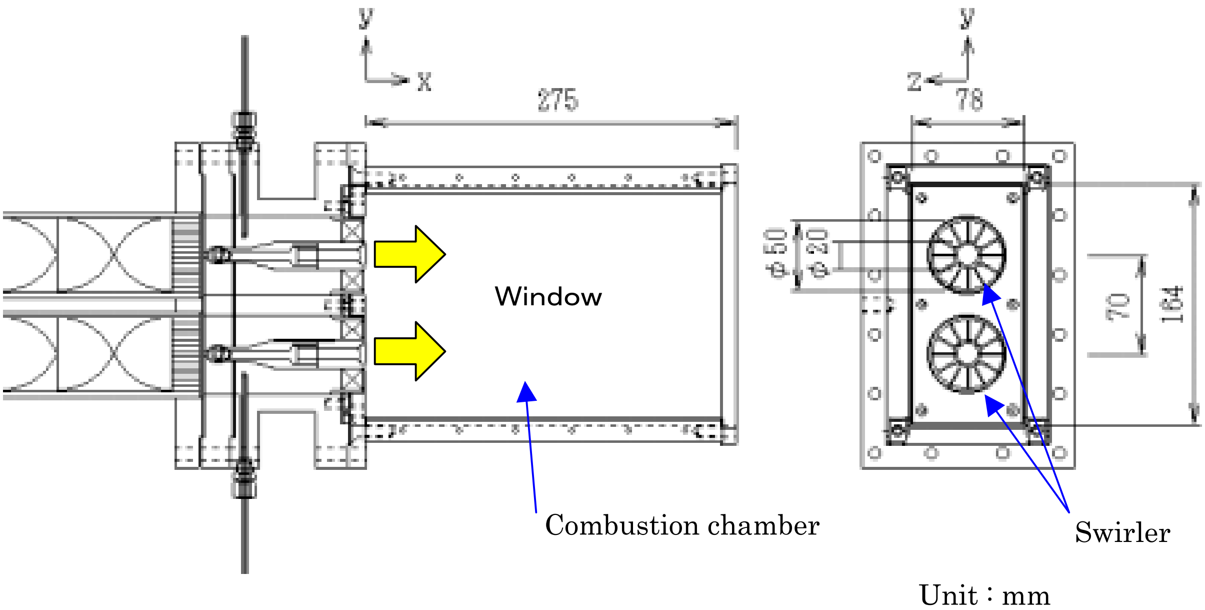


Fig. 2 Combustor model

measurements of various kinds of fuel supplying method. It has two sets of fuel supply system. Each system has fuel injector for premixed combustion, long mixer and swirler with another fuel injector for diffusion combustion. Each swirler is counterclockwise. In this research two systems were adjusted to supply mixtures in the same conditions. The mixture of methane and air comes from left side through the mixer and flows into the combustion chamber from swirler. The chamber has four windows (Top, bottom and two sides).

2.2 Measurement Systems

The ICCD camera is ORIEL / InstaSpecV 77195. Two optical filters, a band-pass one (Andover / 313FS10-50) and a visible-ray-absorption one (Sigma Koki / UTVAF-50S-34U) are used. The components of the PIV system used are a dual pulse Nd:YAG laser (Spectra-Physics / Quanta-Ray PIV-400) with a laser light sheet optical set, a synchronizer (TSI/Laser Pulse 610032), a cross-correlation CCD camera (TSI / PIVCAM 10-30 630046) and PIV software (TSI / Insight NT Ver.3.0). Straddling time is set to 5 microseconds.

Scopes of OH radical chemiluminous intensity measurement and PIV is shown in Fig. 3. Each CCD camera is located at the side of combustion chamber. OH radical chemiluminous intensity data are summed up in z-direction. Velocity distribution obtained by PIV is in the symmetry plane.

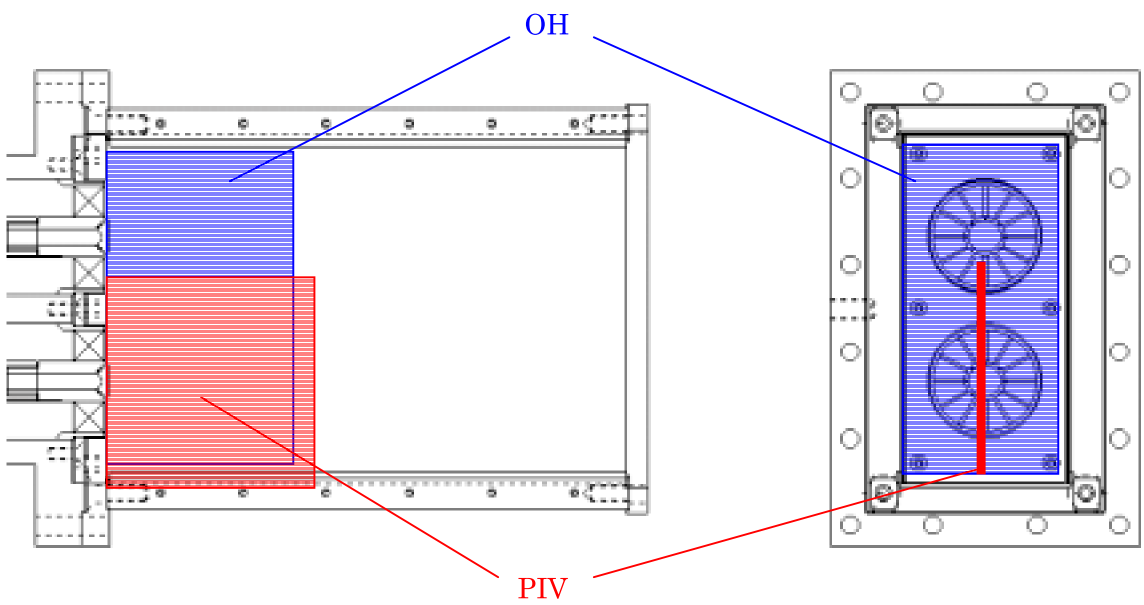


Fig. 3 Scope of measurement

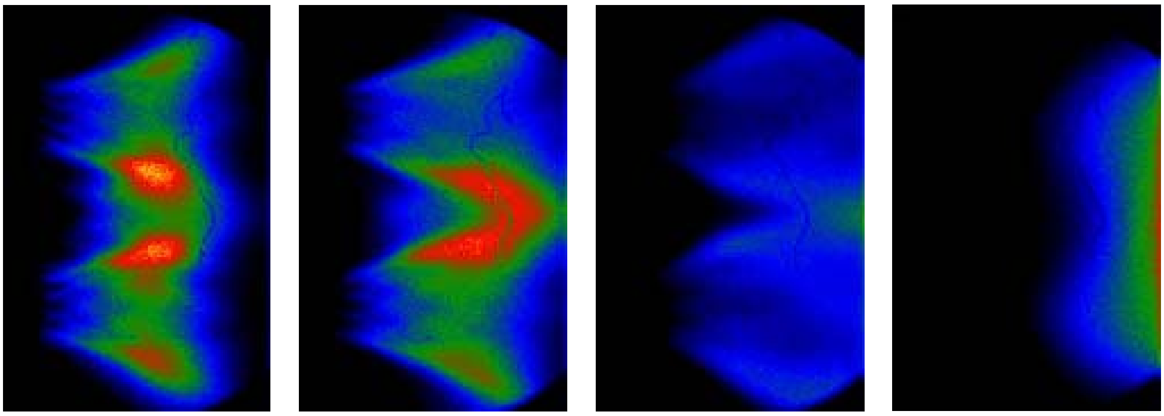
3. Results and Discussions

At the beginning, combustion characteristic of the combustor model was examined. The bulk velocity of the swirler was adjusted to 30 m/s. Mixture was heated up to 600 K. Observation of the flame was conducted in varying the equivalence ratio. From this experiment, it was found that blow off occurs about 0.45, flame is detached from the swirler at

0.56 and oscillatory combustion arises at 0.8. The flame behavior near the lean limit and oscillatory combustion at high equivalence ratio were measured. Our Working Group is dealing with the lean combustion. But oscillatory combustion often appears at low equivalence ratio in combustors, especially in high-pressure condition. It is important to develop the measurement systems of the oscillatory combustion and to understand its mechanism.

3.1 Near the Lean Limit

Figure 4 shows OH chemiluminous intensity distribution in different equivalence ratio. The main flow direction is from left to right. Each dataset is summation of many shots. The exposure time of one shot is 13 microseconds. The number of shot is shown in the second line. As the equivalence ratio decreases, the intensity becomes low rapidly and intensity distribution changes its shape. When equivalence ratio is 0.7, the flame is very active and high intensity area is very short. Reaction starts in the wake of the swirler blade. In the condition of 0.6, most intense area is downstream comparing to that of 0.7 and high intensity area is longer. When 0.5, flame is apart from swirler and flame front is formed in the surface, which has low velocity enough for flame propagation. When 0.45, flame is apart from recirculation zone and most fuel is consumed outside of combustion chamber.



(a) E.R.=0.7 570 shots (x1)

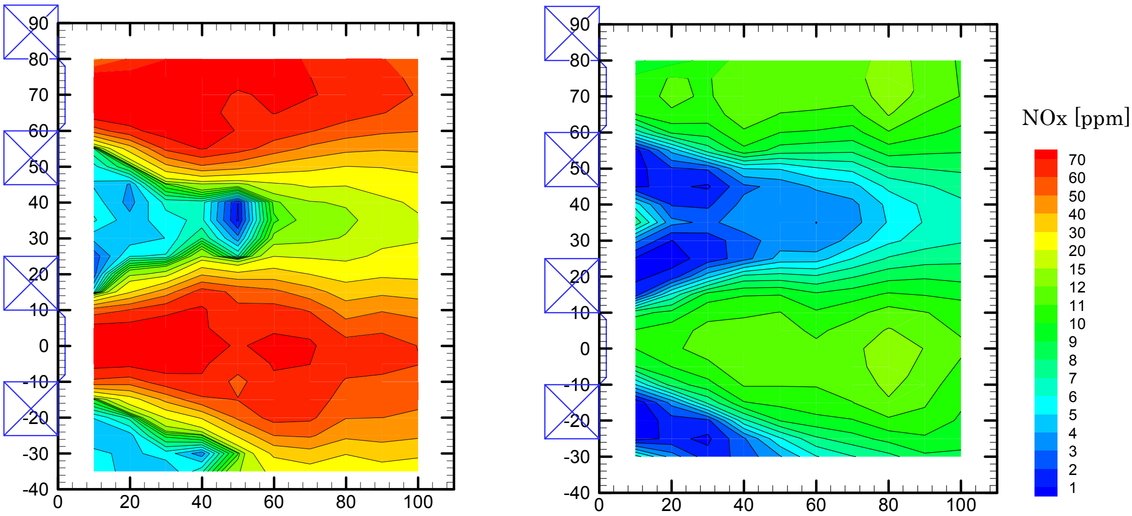
(b) E.R.=0.6 1710 shots (x3)

(c) E.R.=0.5 3420 shots (x6)

(d) E.R.=0.45 13680 shots (x24)

Fig. 4 OH chemiluminous intensity distribution of different equivalence ratio

These results show that a pilot flame is effective for steady flame holding. Most of present lean premixed combustors have diffusion pilot burner. Kurosawa et al., (2001), compare NOx concentration distributions of premixed combustion with diffusion pilot and without that (Fig. 5). They concluded that the addition of a small diffusion flame increases much NOx emission in the premixed flame. Therefore a premixed pilot flame is preferable. Attention has to be paid to its stability. Fig.4 shows that equivalence ratio of pilot flame must be greater than 0.6 for steady flame holding in the conditions of this research.



(a) Premixed: 80%, diffusion: 20%

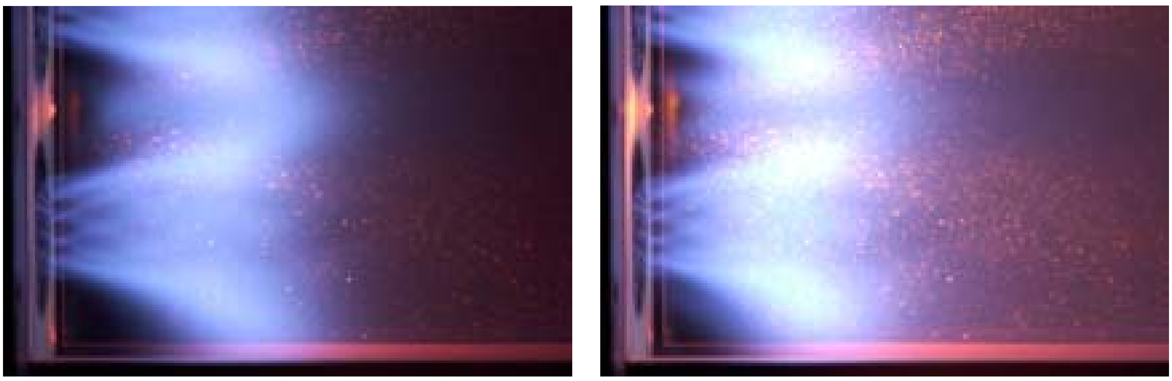
(b) Premixed: 100%

Fig. 5 NOx concentration distributions (mixture temperature is 400K)

3.2 Oscillatory Combustion

Very intense oscillatory combustion occurs, when equivalence ratio is 0.8. The frequency of the oscillation is about 600 Hz from FFT analysis of sound. It corresponds to a fundamental wave in the combustion chamber.

Figure 6 compares the visible flames of stable combustion and oscillatory one. Camera settings are the same. Flame shapes and flow patterns are very similar, though oscillatory flame is brighter than a stable one.



(a) Stable combustion (E.R.=0.7)

(b) Oscillatory combustion (E.R.=0.8)

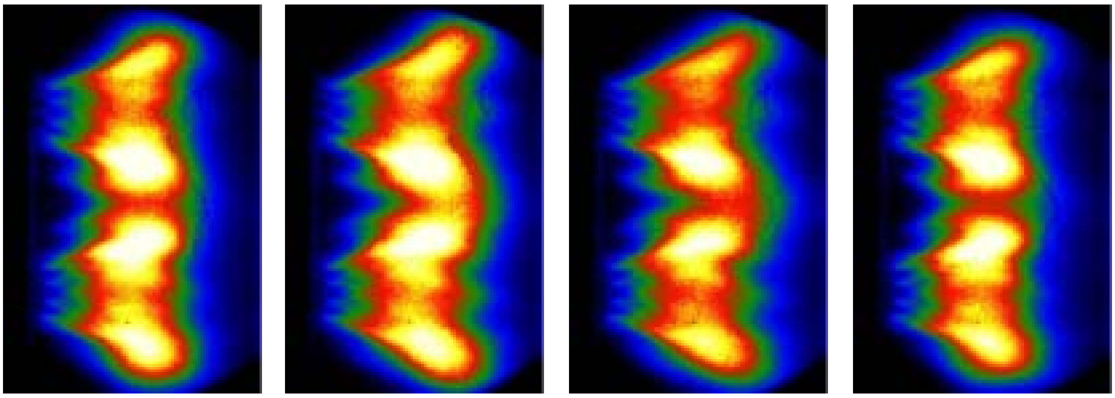
Fig 6. Photographs of flame

Figure 7 shows the OH chemiluminous intensity distribution of stable combustion and oscillatory one. Both (a) and (b) are the summation of 570 shots. The intensity of oscillatory combustion is much higher than that of stable one and the flame front is nearer.

Figure 8 shows OH chemiluminous intensity distribution at intervals of 90 degree of oscillation cycle. Trigger signal to the ICCD camera was made based on the output of microphone placed outside of combustion chamber. Therefore the phase difference between

(a) Stable combustion (E.R.=0.7)　　(b) Oscillatory combustion (E.R.=0.8)

Fig 7.　OH Chemiluminous intensity distribution of different equivalence ratio

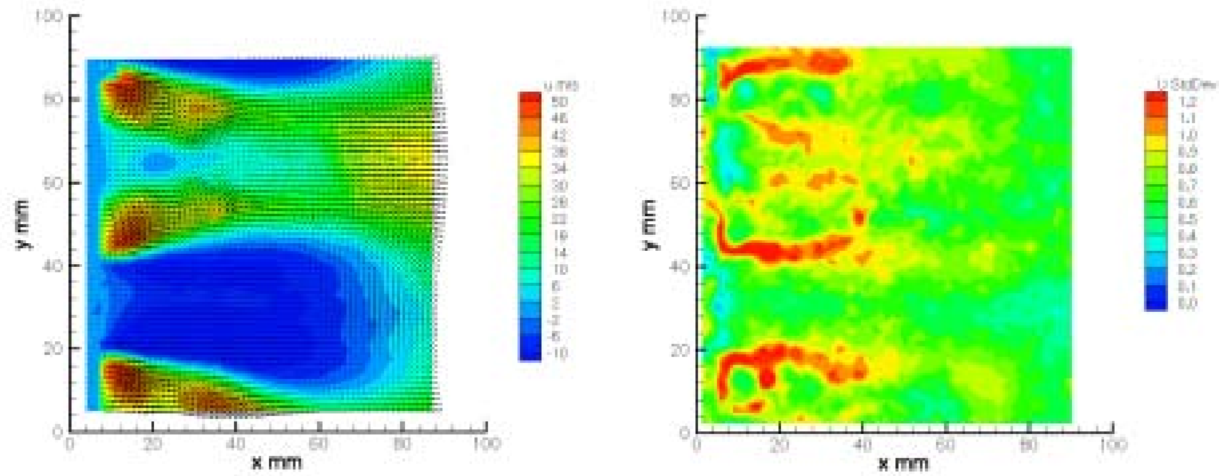


(a) No delay　　(b) 90 deg. delay　　(c) 180 deg. delay　　(d) 270 deg. delay

Fig. 8　OH Chemiluminous intensity distribution at four phases

the pressure in the combustion chamber and OH picture cannot be calculated with enough accuracy. Figure 8 (b) seems to be nearest to the phase of maximum OH intensity.

Figure 9 (a) shows the velocity vectors and distribution of the velocity component in



(a) Average velocity distribution　　(b) Standard deviation distribution

Fig. 9　Velocity component in x-direction and its standard deviation x-direction measured by the PIV system. Figure 9 (b) is the standard deviation distribution of the velocity component in x-direction. Comparison of figure 9 (a) and (b) shows that the high value is distributed in shear regions between the jet from the swirler and the recirculation zone. Here is also flame region. The maximum value of the standard deviation is very low and this value includes the fluctuation due to the turbulence. It shows that velocity fluctuation is very small. The reason is easily supposed that the fluid cannot follow the pressure with high frequency fluctuation. However there is no report that shows the velocity measurement on the oscillatory combustion as far as we know.

4. Demonstration Combustor

Based on the result of measurement, a demonstration combustor is designed. Figure 10 shows the concept of the combustor with a full set of active control devices. It has several characteristics shown bellow.

Passive controls

(1) Premixed pilot burner: Premixed combustion is selected for the pilot burner. The equivalence ratio is changed actively.

(2) Conical flame holder: It is difficult to propagate the flame to radial direction by swirler type flame holder. Conical flame holder has possibility to do that.

Sensors for active control

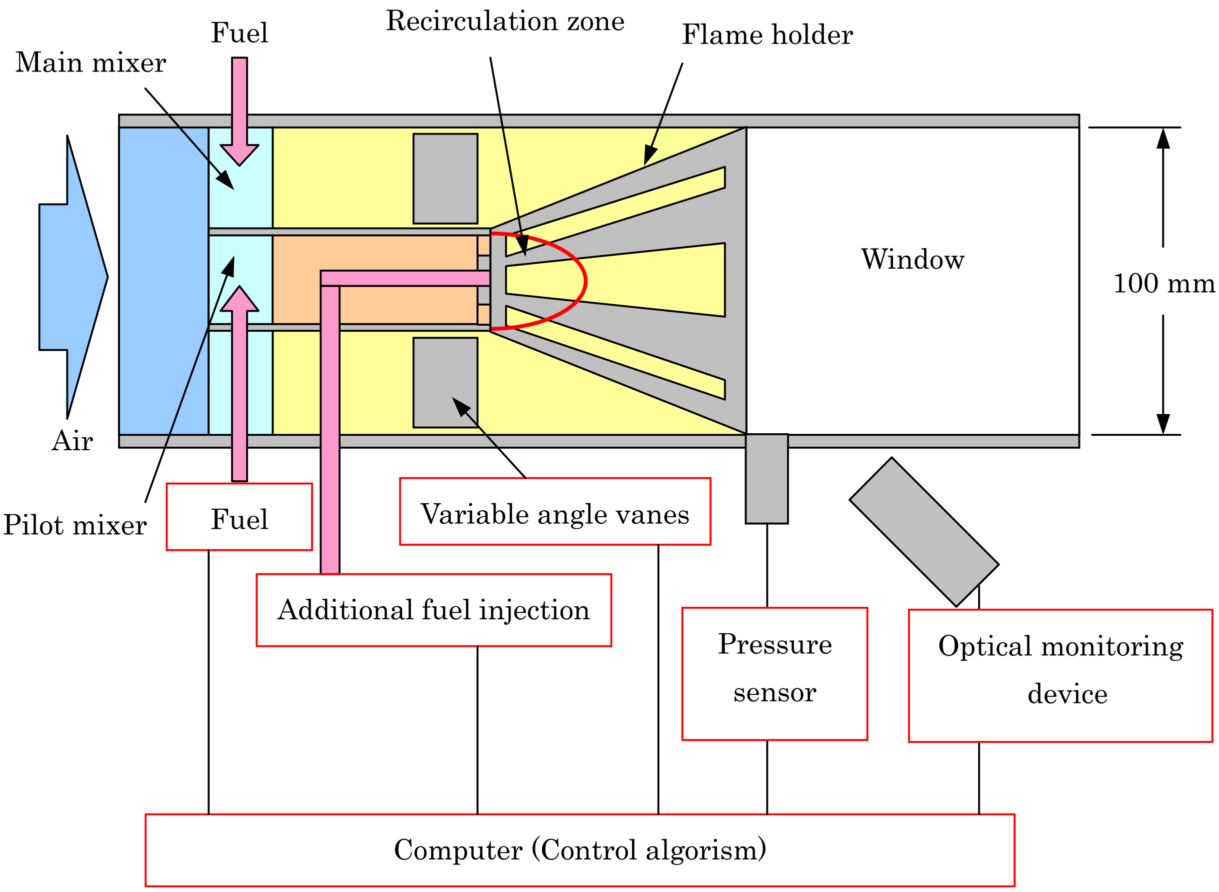


Fig. 10 Concept of new combustor

(3) Optical monitoring device: The state of flame is obtained by the chemiluminescence of the radical species.

(4) Piezo-electric pressure transducer: High frequency pressure fluctuation is measured.

Actuators for active control

(5) Variable angle vanes: Turbulent intensity affects combustion rate. The variable angle vanes control the turbulent intensity and size of the recirculation zone. They do trade-off between the pressure loss and the turbulent intensity.

(6) Additional fuel injection: It is used to attenuate the oscillatory combustion.

5. Summary

OH chemiluminous intensity and velocity distributions were measured to investigate the combustion instabilities in a swirl type combustor. The stable flame is held by the wake of the swirler blade and the recirculation flow formed by swirler. In near lean limit condition, the reaction zone moved downstream as equivalence ratio decreased. The zone was apart from swirler, when equivalence ratio is lesser than 0.5. It shows that the pilot burner needs 0.6 at least in same conditions with this study. In the oscillatory combustion condition, the OH chemiluminous intensity distributions at four phases of oscillation were captured. The ICCD camera triggering system based on the sound is verified. The result of PIV measurements showed that oscillatory combustion with high frequency has very small velocity fluctuation and only the heat release rate changes. Based on the results, the demonstration combustor was designed and manufactured. It has a premixed pilot burner, conical flame holder and variable angle vanes.

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