The Effects of Secondary Fuel Injection on Combustion Oscillation

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Abstract

The purpose of this work is to develop an effective active control system for combustion instabilities of premixed combustors. For the first step, the natural modes of combustion oscillation were investigated for a methane-air premixed combustor and the controls by secondary fuel injection were examined. The main premixed flame is stabilized by a swirler with orifices for secondary injection installed on the central hub. For sensing purposes, a pressure transducer and a chemiluminescence sensor were placed on the appropriate positions. The acoustic characteristics and the source of the oscillation were analyzed by those signals. To test the controllability, two methods of actuations by secondary fuel injection were examined. One is the open loop control and the other is the closed loop control. The comparison of the reduction levels of p'_{rms} shows that the closed loop control with a phase-shift injection performs best in this condition.

Introduction

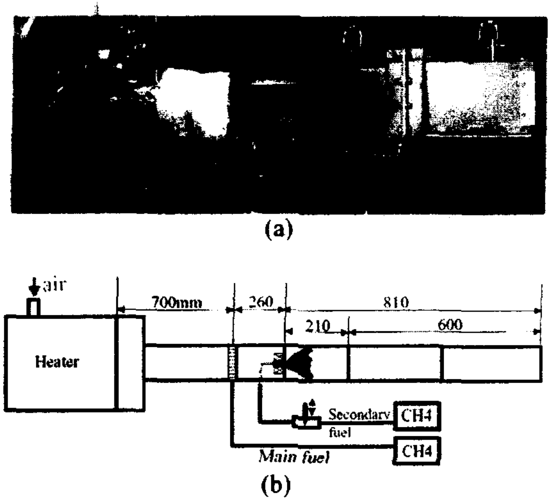
Lean premixed combustion has been considered as a promising way to reduce NOx emissions and continuous efforts to build it in the real gas turbine system has been exerted. However, the realization has not been completed yet for some reasons. One main drawback that prevents the realization is the instability of premixed flames. To overcome the difficulties, passive controls have been adopted to the development of each combustor. In recent days, from the point of view of adaptive flexibility of the control, active control has begun to attract attention.

The source of the instability is coming from the mutual interaction between fluctuations of pressure and heat-release rate. Hence, for sensors and actuators, there are two standpoints correspond to each of the components of the instability. Usually, pressure transducers and chemiluminescence detectors are used for sensing pressure and heat-release rate respectively[1-3]. In a similar way, loud speakers[4,5] and secondary fuel injections are used for the actuation[2,6]. From the point of view of application to the real-scale combustor, the actuating power generated by loud speakers may be too low. Consequently, the secondary fuel injection is considered to be the realistic way for the actuation. In this paper, we employ a pressure transducer and a chemiluminescence detector as the sensors and secondary fuel injection as an actuator. The acoustic characteristics of the combustor are analyzed by signals from the both sensors. And two types of actuations by secondary fuel injection are examined and discussed on the effects on the instability.

Experimental setup

Combustion test rig

Fig.1a,b show the picture and the schematic of the combustor system respectively. The system is composed of an air supply, an electric heater of 130kW, a main fuel mixer and a combustion chamber. An upstream part of the chamber is built of crystal glass plates so as to access optically inside of the chamber. As a flame holder, a swirler with secondary injection orifices is employed. The schematic is illustrated in Fig2. Outer and inner diameters of the swirler are 50mm and 20mm respectively. And it composed of 12 vanes of 30 deg angles and 8 injection orifices of 1.4mm diameter with 30 deg angles. The injection orifices are installed on the central hub.



(a)

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Fig.1 Combustion test rig (a) Picture and (b) Schematic

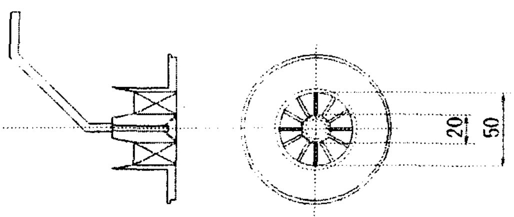
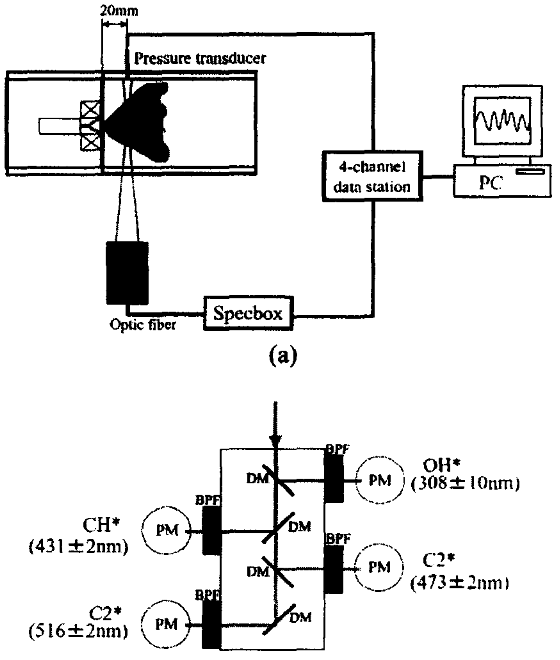


Fig.2 Swirler with secondary injection orifices

Measurement system

Measurement system for pressure and chemiluminescence is illustrated in Fig.3a. A pressure transducer (Kulite Semiconductor Products, Inc., Model XTME-190-25G) is placed on the chamber wall at 20 mm downstream from the inlet. A double condenser lens of 300mm focal length is placed on outside of the glass window at the opposite position to pressure sensor. The collecting light is focused on the optic fiber and transmitted to Specbox. Specbox is the equipment to sift the incident light into four band-passed wavelengths$^{3)}$. The components of Specbox are shown in Fig.3b. In this paper, we use only CH* signal. A multi-channel data acquisition system (ONO SOKKI, DS-200, Graduo) is used for the simultaneous measurements of pressure and chemiluminescence. Typical sampling frequency is 10kHz for each channel.



(a)

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Fig.3 (a) Measurement system, (b) Components of Specbox

Results and discussions

Acoustic modes of the combustor

Natural modes of oscillation of the combustor were investigated for the condition of T_{air} = 500K and U_{swl} =12m/s. In this case, no secondary fuel was injected, thus ER_t = ER_m. As equivalence ratio increase, combustion oscillation arises at some point. We can find the occurrence by the change in amplitude of the pressure fluctuations. In Fig.4 shows pressure fluctuations and Rayleigh correlation integrals with increasing equivalence ratio. From the both, it can be seen clearly that the transition occurs at $ER_m \sim 0.67$. The Rayleigh correlation integrals R is defined by analogy with the Rayleigh index as follows:

$$R = \frac{1}{N}\int_{N\tau} p'(t) \cdot I'_{CH*}(t)dt \qquad (1)$$

Here, p' is pressure fluctuation at one point and I'_{CH*} is the accumulated value of CH* intensity over the measurement volume. Hence we made assumptions that the I'_{CH*} has linear dependency on the global heat release rate fluctuations and pressure distribution in space is uniform over the volume. τ is the period of time for one cycle of oscillation. N is the number of cycles to be averaged. The correlation integrals show similar trend with pressure fluctuations. It indicates the oscillation is driven by thermo-acoustic interaction.

The power spectrum densities of pressure fluctuations for different ER conditions are shown in Fig.5. The highest peaks around 200Hz are corresponding to 1/4 acoustic mode of the length of the combustion chamber. The second highest peaks around 600Hz are corresponding to 3/4 modes of the basic harmonics. The lower peaks around 400Hz and 800Hz are the higher harmonics which are due to the distortion of the basic wave from completely sinusoidal.

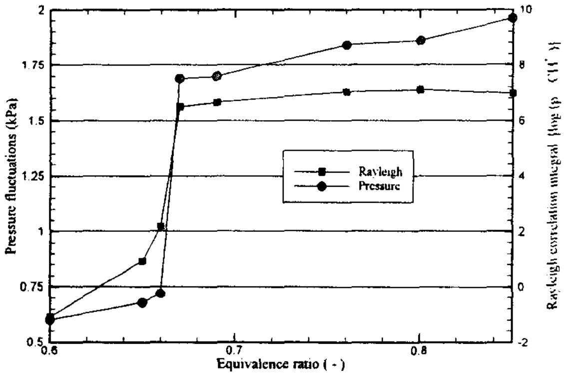

Fig.4 Transition to combustion oscillation

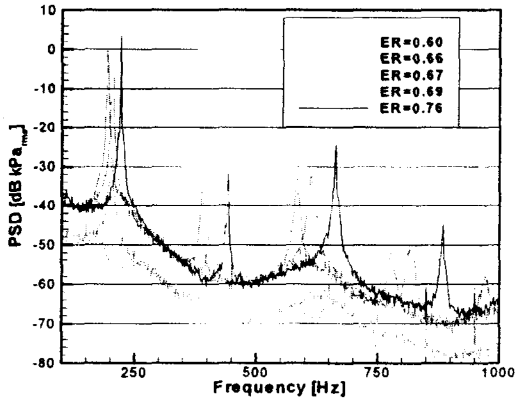

Fig.5 Power spectrum densities of p' (natural modes)

The effects of secondary fuel injection

To examine the controllability of secondary fuel injection method, we apply a phase shift approach. The schematic of the approach is shown in Fig.6. First, the signal from the pressure transducer is put through a band-pass filter. Next, the triggering signal is generated when a positive slope above zero is detected. Then by imposing delay time and open width, the command pulses in voltage are generated. The command pulses are transformed into actuating current for the solenoid bulb. This closed loop of control was carried out by manually setting the central frequency for band-pass filter, trigger points, delay time and open width.

Fig.7 shows a time sequence of pressure fluctuations with switching the control on/off. The baseline conditions with no secondary injection, thus control-off, is T_{air} =500K and ER_t = ER_m = 0.77. In this condition, the natural modes of oscillation are occurring. When the control switch is on, thus when the secondary fuel is injected, total equivalence ratio ER_t becomes 0.85 and the amount of the secondary fuel against main fuel is about 10%. The comparison of spectra between three conditions is shown in Fig.8. 'Open' means the secondary fuel being injected constantly in an open loop manner and 'Closed' means the bulb is working in the closed-loop manner of phase-shifting pulsation described above. In this case, the central frequency for band-pass filter is set to 220 Hz which corresponds to 1/4 mode. The delay time and open width are set at the value of 0.125 and 0.6 msec respectively. Reduction of peaks by the controls is obvious for all the harmonics. If we focus attention on the highest peaks, it can be seen that more effective reduction was achieved by the closed loop than by the open loops. In Table.1 shows p'_{rms} for each case. The reduction percentages of p'_{rms} to the no-control case are 59.7 % for the open loop and 72.3 % for the closed loop.

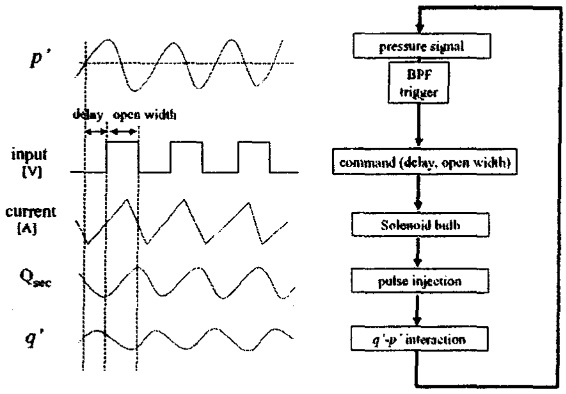

Fig.6 Schematic of the phase shift approch

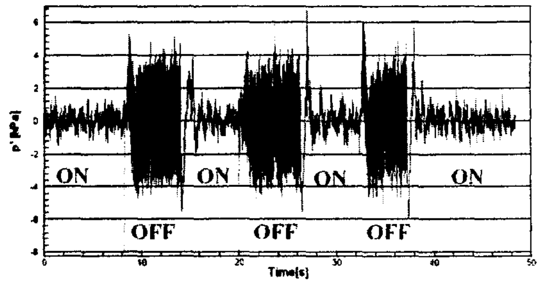

Fig.7 An example of time sequences of pressure fluctuation

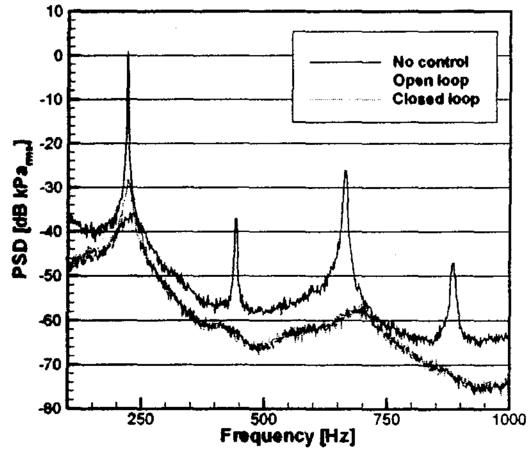

Fig.8 Power spectrum densities of p' with/without control

Table.1

Control	p'_{rms}[kPa]	Reduction[%]
No	1.91	—
Open loop	0.77	59.7
Closed loop	0.53	72.3

Conclusions

The natural modes of combustion oscillation were investigated for a swirl-stabilized combustor. On the condition of T_{air} = 500K and U_{swl} =12m/s, the oscillation begins at ER~0.67 and the frequencies of the highest peaks were found to be the 1/4 primary mode of the chamber length.

The effects of secondary fuel injection on the oscillation were examined by two ways. The reduction percentages of p'_{rms} to the no-control case are 59.7 % by the constant injection in the open loop manner and 72.3 % by the pulse injection in the closed loop manner. Hence, the pulse injection method with the phase-shift approach is considered to be an efficient actuation for the active control of combustion oscillation.

Acknowledgement

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