An Investigation of the Modulation of Equivalence Ratio at the Fuel Injection Hole

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1 Introduction

Many gas turbine operators have reported low-frequency pressure fluctuation during the change of combustion load and near flammability limits. It is expected that the low-frequency pressure fluctuation is connected to flame destabilization due to changes of local equivalence ratio or flow conditions and that this fluctuation occurs readily near the lean limit and during load change process. Regarding the low-frequency pressure fluctuation, it is noticeable that many real gas turbine combustors operate under unchoked fuel flow condition, which can be affected by the pressure fluctuations of combustion chambers. In unchoked condition, interaction between fuel flow and pressure fluctuation can result in modulation of the fuel flow. This in turn brings changes to the spatial and temporal equivalence ratios, as both spatial and temporal heat production are highly related to pressure fluctuation.

2 Experimental setup and method

Figure 1 illustrates the experimental setup, which consists of three parts: a combustor, mass flow control devices for fuel and air, and pressure measurement and flame imaging systems. The combustion chamber is made of a quartz tube for visualization of a flame and its overall length is 700 mm. The fuel supplying system is consisted of concentric tubes which have fuel supplying holes. Dried air is introduced at the bottom of the tube and the fuel (LPG) is injected to the air stream through four fuel supplying holes. Two fuel supply conditions were adjusted by varying the diameter of the fuel holes: 0.7 mm diameter holes in the case of unchoked fuel and 0.3 mm diameter holes in the choked fuel. The injected fuel mixes with the air as it passes through the mixing distance (L_{fuel}). The mixture passes through the swirler immediately before the dump plane, and then finally reaches the combustion chamber. The swirler is located in the mixing section using vanes positioned at an angle of 45°.

For measurement of the dynamic pressure of the combustion chamber at the dump plane (P (7) in Fig. 1), we used a piezoelectric pressure sensor PCB Model 106B; the sensibility of the 106B model is 44 mV per 1 kPa and its dynamic range is from 0.5 Hz to 40 kHz in response time. Images of flame shapes were taken by a digital camera (Nikon, COOLPIX 995) and a camcorder (SONY, DCR-TRV 300). Phase resolved images were acquired using a high speed ICCD camera (Phantom V7.0) with 0.02 milliseconds time resolution. Figure 3 illustrates the schematic diagram of gas sampling system to investigate the modulated equivalence ratio in accordance with pressure fluctuations of combustion chamber. For sampling of unburned mixture at the fuel supplying holes, we used a high speed solenoid valve (Parker series, S/N 78) with 2 milliseconds response time. The solenoid valve was actuated by a pulse delay generator (BNC 555-4C), and its duration time was 20 milliseconds. Sampled mixtures in phased with pressure fluctuations of combustion chamber were analyzed quantitatively by a gas chromatography (Agilent 6890N).

3 Fuel flow modulation with pressure fluctuations

In Fig. 2 (c), the pressure signal looks like some beating phenomena. High Intensified CCD (HICCD) camera was taken with the triggered pressure signal. From the results we can divide the pressure fluctuation into two cycles; A-cycle and B-cycle. In the A-cycle, flame images and pressure fluctuated with a frequency about 200 Hz and flame stabilizes near the dump plane (region I). In the B-cycle, the flame does not exist in the region (I) and it stabilizes far from the dump plane (region II) and the level of pressure fluctuation becomes diminished. The pressure signal can be divided into noisy region of 200 Hz fluctuation (A-cycle) and silent region which has small pressure fluctuation (B-cycle), and these two regions are repeated periodically at a frequency about 10 Hz and the period is 100 ms. As mentioned before the flame of the 200 Hz fluctuating region exists in the region (I) and region (II) and the flame of the silent region exists only in the region (II). The difference of the flame stabilization location results from the equivalence ratio fluctuation due to the fuel flow modulation. In the unchoked condition, the pressure boundary of the fuel injection nozzle is affected by the pressure fluctuation transferred from the combustion zone. Therefore the equivalence ratio is fluctuating with the amount of the fuel over time.

4 Experimental results

As a result, the equivalence is 0.26 in the case of the large pressure fluctuation and 0.78 in the case of the small pressure fluctuation. The modulated equivalence ratio in a noisy period of the large pressure fluctuation becomes 50% of the inlet equivalence ratio. When this modulated equivalence ratio feeds the combustion chamber, the flame moves to the downstream of combustion chamber. Therefore the silent period with little pressure fluctuation could exist. The equivalence ratio is higher than the inlet equivalence ratio because the clogged fuel of the noisy period is injected as well as the inlet fuel flow rate of the silent period. Figure 4 shows the quantitative result of the modulated equivalence ratio.

5 Numerical simulations

For numerical simulation, this model was calculated quantitatively with the Computational Fluid Dynamics (CFD) which is STAR-CD v.3.26 in order to understand how the equivalence ratio is modulated depending on unchoked condition when the pressure fluctuation of 10kPa propagates to the combustion chamber. For boundary condition, the upper outlet part is designated the pressure boundary like Fig. 5 (left). The hole exists at 221mm below from pressure boundary and the length of total geometric shape becomes 288mm. We used the cylindrical coordinate system, and the origin locates at 288mm above from the end of the fuel feeding side in the fuel channel. Let's consider the mixing point of the fuel and the oxidizer as hole (2), and the channel with (1) and (3) as the mixture channel and fuel channel, respectively. Figure 5 (right) shows the 3-dimensional geometry to know the 2-dimensional geometry easily. The quarter cyclic boundary condition applied at both sides of the channel.

As a result, figure 6 shows the variation of equivalence ratio for 0.5 second in the model which was satisfied with unchoked condition. The equivalence ratio has range of 0.37~0.7 according to time. This result shows that modulated mass flow rate at fuel injection hole with unchoked condition by pressure fluctuation occurs oscillation of equivalence ratio in mixture flow channel. These data support to explain the flame behavior in mode 2 and the characteristics of the pressure fluctuation.

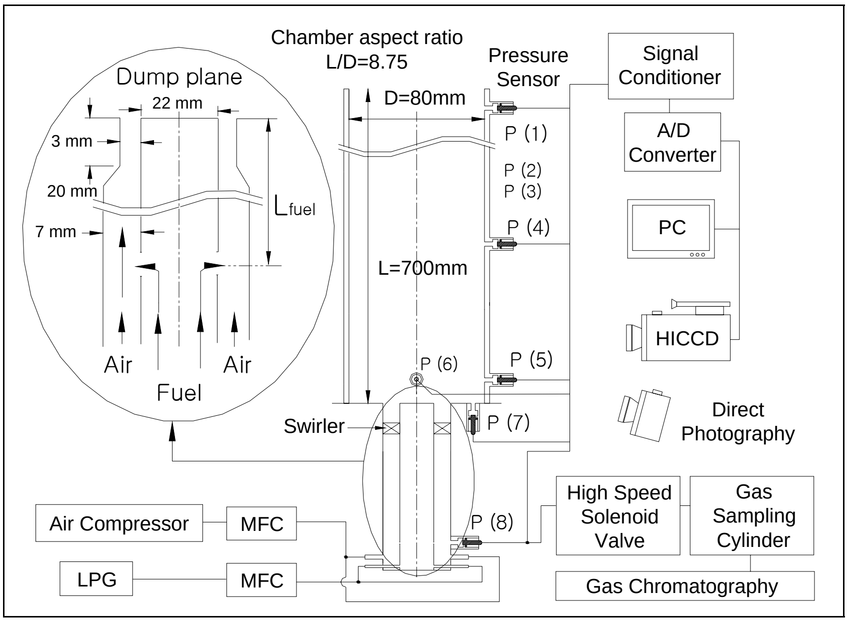
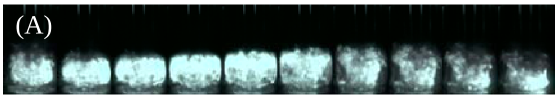
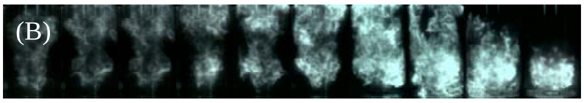


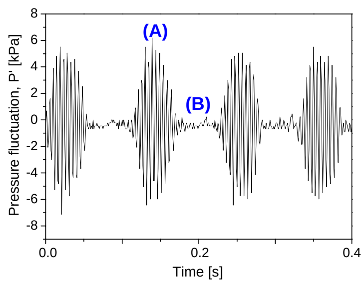
Fig. 1 Schematic diagram of the experimental apparatus



(a) HICCD images of noisy period for 5 ms



(b) HICCD images of silent period for 50 ms



(c) Pressure signal in time domain

Fig. 2 High speed Intensified CCD images and pressure signal (Ø = 0.55, L_{fuel} = 285 mm): (a) HICCD images of noisy period for 5 ms, (b) HICCD images of silent period for 50 ms and (c) Pressure signal in time domain

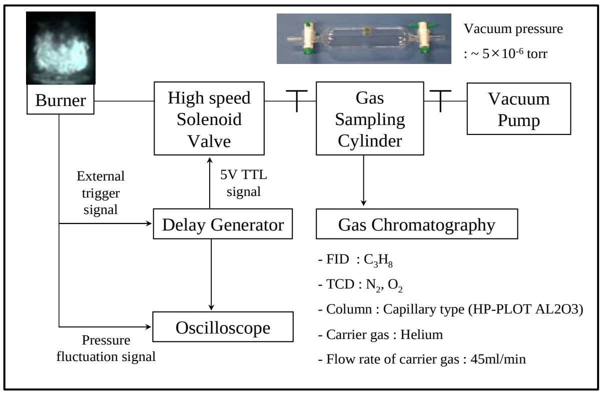


Fig. 3 Schematic diagram of gas sampling system

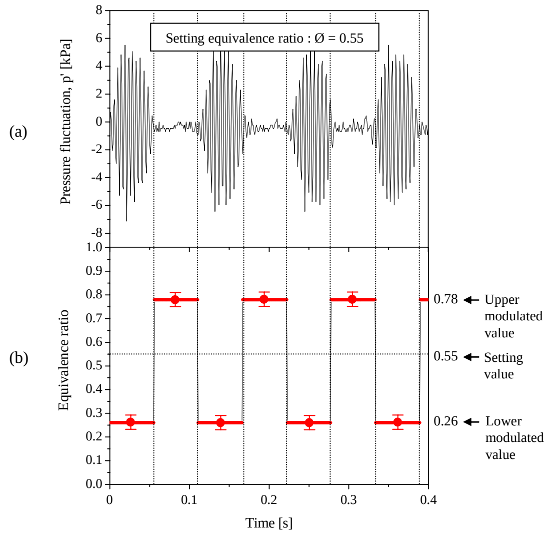


Fig. 4 Modulated equivalence ratio with respect to pressure fluctuation: (a) Pressure fluctuation in the combustion chamber. (b) Modulated equivalence ratio at the fuel supplying holes.

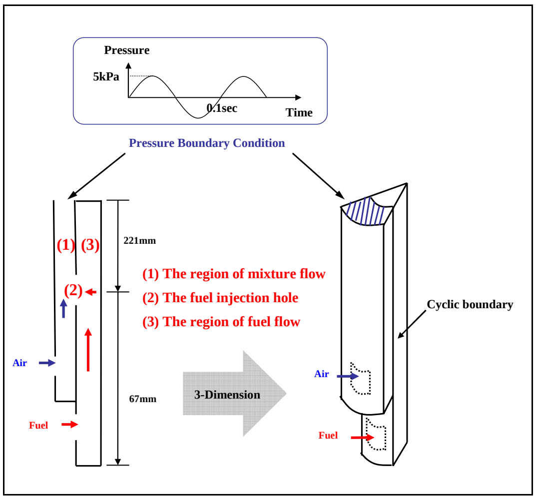


Fig. 5 Schematic diagram for boundary conditions

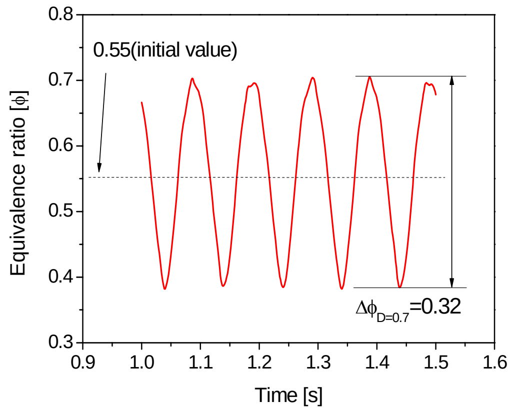


Fig. 6 Time records of equivalence ratio fluctuation

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