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An Experimental Study on the Causes of the Combustion Instability in a Dump Combustor

Jung Goo Hong[1], Min Chul Lee[2], Uen Do Lee[1], Kwang Chul Oh[3], Hyun Dong Shin[1*], Atsushi Maekawa[4], Katsunori Tanaka[4] & Kentaro Fujii[4]

[1]Department of Mechanical Engineering, KAIST, Korea
[2]Korea Electric Power Research Institute
[3]Korea Automotive Technology Institute
[4]Mitsubishi Heavy Industries, Ltd., Japan

Abstract: The stabilization of turbulent flames, together with the emission of combustion products, is the most important problem of the gas turbine combustor. In this study, we made a model gas turbine combustor which has a dump plane and investigated the combustion phenomena with various experimental conditions such as the variation of equivalence ratio, various mixing process of the fuel and air, and fuel injection method. The heat release rate of the flame, the stabilization region of the flame, and the pressure fluctuation of the flow are closely connected to one another in the instability mechanism. We changed the fuel flow modulation, the heat release rate with the load change of the gas turbine and the equivalence ratio variation of the mixing process. We found that the role of the vortex flow near the flame, the modulation of the reactant flow and the flame stabilization mechanism are the key parameters of the combustion instability of the gas turbine combustor.

Keywords: Combustion Instability, Equivalence Ratio Fluctuation, Unmixedness, Vortex

Nomenclature

L_{fuel} distance from dump plane to the fuel injection location [mm]
p' pressure fluctuation [kPa]
q' heat release rate fluctuation
ϕ' equivalence ratio fluctuation

1. Introduction

Diffusion combustion drives an increase in local temperature of a flame region and a rapid rise in thermal NOx which is affected by locally high flame temperature. To complement the increase of NOx emission, multistage combustion is used with the secondary air for cooling and dilution in commercial combustors. Nonetheless, if the NOx emission is not reduced, a selective catalytic reduction (SCR) system must be installed with a considerable financial burden. Especially, because of a worldwide strict regulation on environment and nations' political attitude on their combustion exhaust material, combustion engineers and researchers should be interested in a premixed flame that has a narrow operating region and requires a delicate treatment, rather than in diffusion flame that has a stable operating condition [1-6]. But this premixed combustion method has many kinds of problems about combustion instability.

* Corresponding Author: Phone: +82 42 869 8829,
Fax: +82 42 869 8820, E-mail: hdshin@kaist.ac.kr

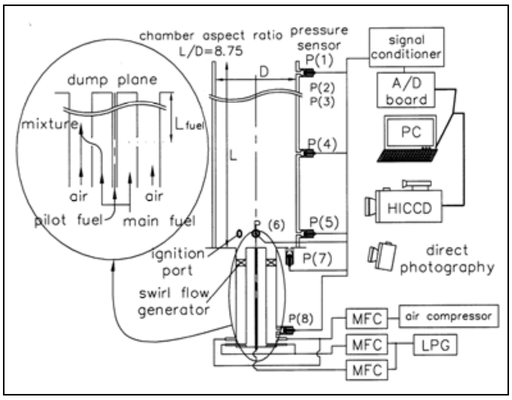
Two of the most valuable researches about this topic are focused on flame-vortex interaction and on time scale influencing periodic pressure variation. First, an instable combustion is due to flame-vortex interaction, which is caused by vortex in relation to shape characteristics of combustor and by flame along vortex. In other words, vortex and flame are very closed both timely and spatially, and flame is dependent upon period and magnitude of vortex. H. Büchner and H. Bockhorn [7] suggested that vortex induced combustion instability is resolved using vortex break by secondary air, etc. Second, T. Lieuwen et. al. [8] insisted that major cause of this heat release rate fluctuation should be equivalence ratio fluctuation, that is, pressure fluctuation due to heat release by periodic combustion transfers upstream, equivalence ratio varies, and it induces heat release rate fluctuation - all this process has a pattern of feedback system coupling. Both researches have a same idea of heat release fluctuation as the cause of instability, but the source of the heat release fluctuation is different. It was difficult to get the general solution of combustion instability and clarify the mechanism because both researches were insisted in a different point of view about the degree of mixing [9] and mixing method between fuel and air.

Thus, we equipped a dump combustor, which can make the fully premixed and partially premixed conditions with a mixing chamber, with an injection system from the fuel to the oxidizer immediately in front of the combustion chamber. Furthermore, we divided the modulation conditions of the choked fuel flow and the unchoked fuel flow in the partially premixed condition; thus, we can deduce that the unmixedness and fuel flow modulation are a source of the equivalence ratio fluctuation. Moreover, our examination revealed that the vortices near the flame zone showed no fluctuation in the equivalence ratio. We therefore sought to know how the fluctuation in the heat release rate affects combustion instability.

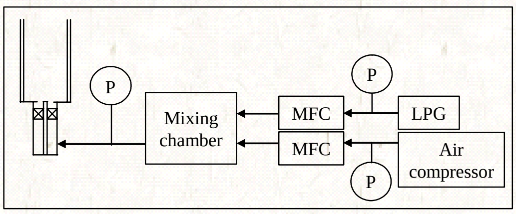
2. Experimental setup and method

Figure 1 shows the experimental setup and method. The dump combustor can be divided by two parts: under the dump plane and over the dump plane. The upper part is a quartz tube for the visualization of the flame. The overall length of the combustion chamber is 700 mm, which corresponds to a nominal L/D of 8.75. To control the flow rate of the fuel and air, we used a mass flow controller. We then injected the fuel though the main fuel injection holes (where the unchoked fuel condition was d = 0.7 mm and 4 holes, and the choked fuel condition was d = 0.3 mm and 4 holes); and the holes were kept apart from the dump plane by a mixing distance (L_{fuel}). Next, we passed the mixture though the swirler just before the dump plane, and it finally reached combustion chamber. The swirl number of swirler is 0.90, which is calculated by the Eq. (1) [10]. The schema in Fig. 1(b) shows that the fuel and oxidizer flow into the mixing chamber and that after they have had enough time to be mixed fully the mixture flows into the combustion chamber.

$$S_n = \frac{2}{3}\left[\frac{1-(D_h/D_n)^3}{1-(D_h/D_n)^2}\right]\tan\theta \quad \text{..........................} \quad (1)$$



(a) Schematic diagram of partially premixed condition



(b) Schematic diagram of fully premixed condition by using mixing chamber

Fig. 1 Schematic diagram of the experimental apparatus

Mixture of LPG and dried air was flowed into the combustion chamber with constant inlet velocity (mean velocity = 21 m/s, Reynolds number = 8850) at the dump plane. The dynamic pressure of combustion chamber was measured at the dump plane by the piezoelectric pressure sensor (PCB Model 106B), and the equivalence ratio and the distance between the dump plane and fuel injection location was varied as experimental parameters.

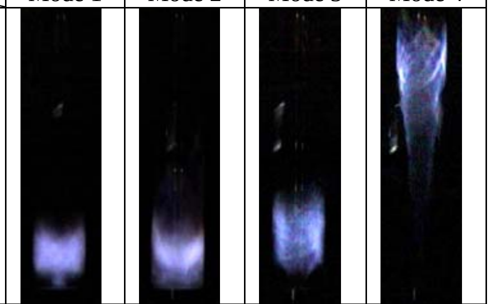
Table 1 Experimental conditions

	Fully premixed	Partially premixed and choked fuel flow	Partially premixed and unchoked fuel flow modulation
Device	Mixing chamber	Fuel injection holes	Fuel injection holes
Dimension	$0.0166m^3$	-	-
Diameter of fuel injection holes	-	0.3 mm	0.7 mm
Number of fuel injection holes	-	4	4
L_{fuel} (mm)	-	94, 158, 221, 285	94, 158, 221, 285

3. Results and discussion

3.1. Unchoked fuel flow modulation

3.1.1. Flame characteristics with respect to equivalence ratio. Figure 2 shows the change of the flame shape with respect to the equivalence ratio change from 1.0 to 0.42 with fixed fuel injection location L_{fuel} = 94 mm.

	Mode 1	Mode 2	Mode 3	Mode 4
Direct photo				
Ø	1.0~0.60	0.60~0.53	0.53~0.44	0.44~0.42
Pressure amp.[kPa]*	8.6	8.5	1.3	1.2

*Peak to peak pressure amplitude

Fig. 2 Photographs of flame

Four representative modes of flame occur according to the equivalence ratio. The pressure fluctuation decreases as the equivalence ratio decreases. As the equivalence ratios increases the flame stabilization zone approaches to the dump plane due to the increase of burning velocity. In addition, when the equivalence ratio is lower than 0.5, the flame length becomes longer and the main reaction zone tends to be far away from the dump plane. Figure 3 shows flow patterns of the combustion chamber. As shown in the figure, the main flow can be divided into two regions: region (I) and region (II). In this experiment, the flame appears in region (I) when the equivalence ratio is higher than 0.5, and the flame stabilizes in region (II) when the equivalence ratio is lower than 0.5. In mode 3, the flame is stable and the pressure fluctuation level is much lower than in modes 1 and 2. In mode 4, the flame lifts off and then blows out when the equivalence ratio is under 0.42. Modes 1 and 2 are characterized by a strong interaction between the acoustic pressure and combustion. In modes 1 and 2, we observed very unstable combustion, high fluctuations of pressure, and loud combustion noise. Thus, we focused on the instability mechanism of mode 1 and mode 2.

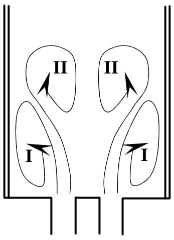
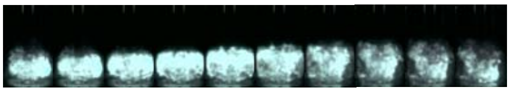
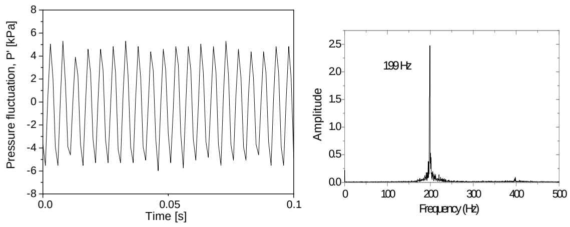


Fig. 3 Coherent vortex structures of mode 1

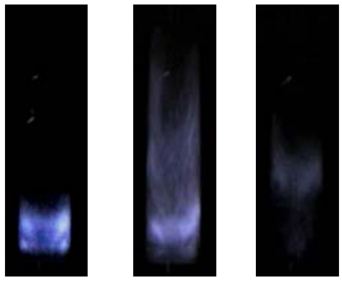

(a) HICCD images of mode 1 for 5 ms

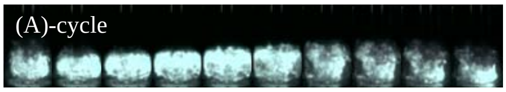


(b)Pressure signal of mode1 in time and frequency domain
Fig. 4 HICCD images and pressure signal of mode 1 (Ø = 0.64)

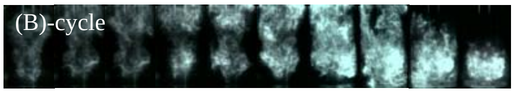
3.1.2 Characteristics of mode 1 and mode 2. In mode 1, the flame periodically burns in the region (I) and we observed the vortical motion of the flame in the region (I) clearly. Figure 4 shows the high speed images of the flame, pressure fluctuation over time and the result of frequency analysis. In this mode, the heat generation was strongly affected by the vortex of the region (I) and it oscillates with 200 Hz. This frequency of dynamic pressure is well match with the resonance frequency of the combustion chamber assuming this system as open to the upward and closed to the downward dump plane, i.e. an open-closed system. In the mode 1, very strong interaction between the acoustic pressure and heat generation occurs and this mode has characteristics of loud noise and vibration. To measure the dynamic pressure, we used a piezoelectric pressure sensor. The peak-to-peak pressure fluctuation was greater than 8.6 kPa, and the sound pressure level, which is based on a minimum audible acoustic pressure of 2×10^{-5} Pa, was 160 dB.

In mode 2, flame alternatively stabilizes in the region (I) and region (II) periodically. When the flame stabilizes in the region (I), the pressure was fluctuated in the same period of mode 1, and when the flame stabilizes in the region (II), the pressure fluctuation becomes negligibly small as the cases of mode 3 and mode 4. Figure 5 shows the alternatively stabilized flame in the mode 2 and figure 6 shows the high speed images and the results of pressure measurements.

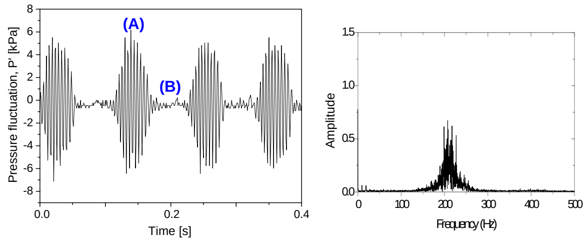

(a) (b) (c)
Fig. 5 Photographs of flame in mode 2 (Ø = 0.55)



(a) HICCD images of 200 Hz fluctuation region for 5 ms



(b) HICCD images of silent region for 50 ms



(c) Pressure signal of mode 2 in time and frequency domain
Fig. 6 HICCD images and pressure signal of mode 2 (L_{fuel} = 285 mm)

In Fig. 6, the pressure signal resembles various beating phenomena. Using a highly intensified CCD camera, we photographed with the triggered pressure signal. From the results, we can divide the pressure fluctuation into two cycles: the A-cycle and B-cycle. In the A-cycle, the flame images and pressure fluctuate at a frequency of about 200 Hz, and the flame stabilizes near the dump plane (region (I)). In the B-cycle, the flame does not exist in region (I) and it stabilizes far from the dump plane (region (II)); in addition, the level of the pressure fluctuation diminishes. The A-cycle and B-cycle continually recur, with a periodic cycle of frequency of about 10 Hz.

3.1.3 Modulation of the fuel flow by pressure fluctuations: the effect of the fuel injection location. Figure 7 shows the pressure fluctuation of the mode 2 in the time domain. The pressure signal can be divided into nosy 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.

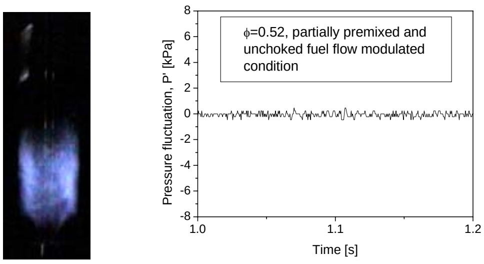
In the case of the mode 1 the pressure fluctuation modulates the fuel flow but the flame can exist in the region (I) because the flame of the lower peak equivalence ratio can stabilize in the region (I). In other words, even though the equivalence ratio fluctuates over time, the mean equivalence ratio is high thus the flame has enough burning velocity to survive in the flow condition of region (I). On the other hand, when the mean equivalence ratio becomes smaller than the mode 1 there is critical equivalence ratio conditions which the flame can stabilize in the region (I) if the mean equivalence ratio does not fluctuate. In this condition, the flame will not be able to stabilize in the region (I) if the equivalence ratio fluctuates. These critical conditions make the mode 2 of this work.

4. The causes of heat release fluctuation and discussion

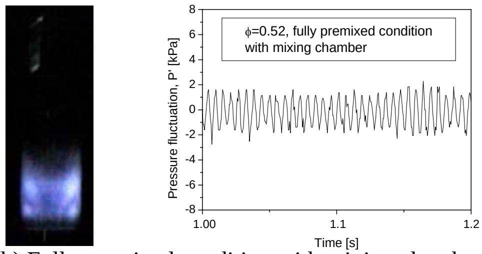
4.1 Fully premixed condition

To compare the fully premixed conditions the partially premixed conditions, and the unchoked fuel flow modulated conditions at the same equivalence ratio (Ø = 0.52), Fig. 7 shows the shape of the flame and the pressure signal. Even though the equivalence ratio is the same, there are differences in the flame's behaviour and the pressure characteristics.

4.1.1 Flame shape and pressure fluctuations. In the fully premixed conditions of Fig. 7(b), where the flame is anchored to the dump plane, most reactions occur in the main reaction zone (vortices I and II). In the case of Fig. 7(a), however, where the flame is distributed in vortex II, the fuel is supplied and mixed with air at a distance of 94 mm from the dump plane; thus, the mixing occurs in the combustion chamber because of the insufficient mixing time.



(a) Partially premixed and unchoked fuel flow modulated condition (L_{fuel} = 94 mm)



(b) Fully premixed condition with mixing chamber

Fig. 7 Photographs of flame and pressure fluctuation signal in time domain (Ø = 0.52)

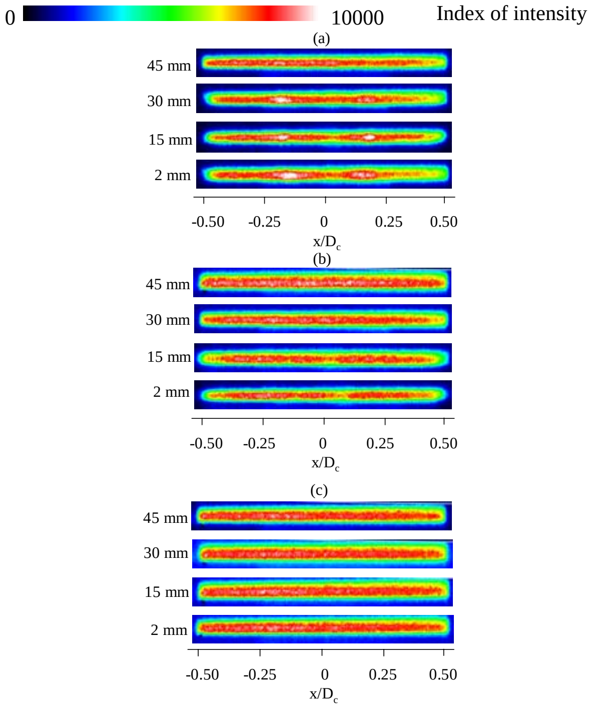


Fig. 8 Acetone LIF images at combustion chamber inlet: (a) L_{fuel} = 94 mm, (b) L_{fuel} = 285 mm, (c) fully premixed with mixing chamber

To evaluate the unmixedness, we measured the laser induced fluorescence of the acetone, which has a similar transport property to propane. Figure 8 shows the unmixedness with respect to L_{fuel} at the entrance of the combustion chamber. The intensity of the unmixedness is as large as L_{fuel} is short because of the short mixing time; it is also as small as L_{fuel} is long because of the longer mixing time. We therefore deduce that when the flow rate and equivalence ratio are the same the degree of pressure fluctuation can be changed by the unmixedness.

4.2 Partially premixed and choked fuel flow condition

For checking the effect of the unmixedness, the fuel flow rate was fixed so that it could not be affected by pressure fluctuation of downstream by choking of fuel flow.

4.2.1 Flame shape and pressure fluctuations. For the choked fuel flow, flame shape is similar to that of mode 1 under the fully premixed condition as shown in Fig. 7

(b). We observed modes 1, 3 and 4 but, in contrast to the unchoked fuel flow, we could not observe mode 2. Because the fuel inlet was choked, the fuel flow was not modulated by the high pressure fluctuation. Thus, mode 2 could not be seen. The equivalence ratio fluctuates in this case, but not as much as it does for the condition of the unchoked fuel inlet because the choked fuel inlet maintains constant injection of fuel.

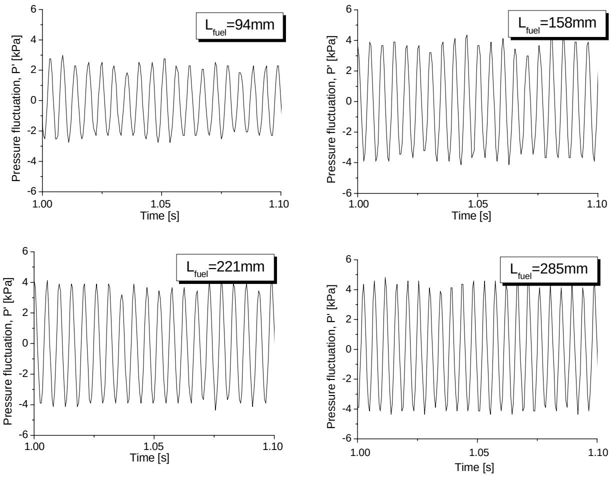


Fig. 9 Pressure fluctuations with fuel injection location in case of choked fuel flow condition (Ø = 0.64)

In the case of choked fuel flow condition, varying the L_{fuel} as 94 mm, 158 mm, 221 mm and 285 mm with constant equivalence ratio of 0.64, the dynamic characteristics of pressure were measured for 0.1 second, as shown in Fig. 9. The frequency of pressure fluctuation was fixed near 200 Hz exactly and oscillation time was 5 milliseconds, but the amplitude of pressure fluctuation gets smaller as the L_{fuel} smaller. In this experiment, the acoustic time scale is small enough to omit when calculating the oscillation time. From the pressure signals of Fig. 9, in the case of choke fuel flow condition, we can conclude that the characteristic time of oscillation is governed by the resonant frequency of 200 Hz, thus 5 milliseconds.

In the case of the choked fuel flow conditions, the unmixedness and the vortex cause the equivalence ratio to fluctuate, and these parameters of pressure fluctuation are two of the three parameters that cause the heat release fluctuation. We therefore need to quantitatively evaluate how each parameter contributes to the pressure fluctuation.

Figure 10 shows the peak-to-peak pressure fluctuations with respect to L_{fuel}. Under the fully premixed conditions, the Peak-to-peak pressure fluctuation was 9.2 kPa; in other cases, it diminished by the degree of <1> as L_{fuel} shortened. Under the choked fuel flow conditions, only the unmixedness caused the equivalence ratio in the combustion chamber to fluctuate because the equivalence ratio did not fluctuate at the fuel exit. As a result, the unmixedness decreased the fluctuation by the degree of <1>. Under the fully premixed conditions, the equivalence ratio did not fluctuate at the fuel exit; furthermore, because the unmixedness of the fuel and air in the combustion chamber caused no fluctuation in the equivalence ratio, we can deduce that the vortex caused the fluctuation by the degree of <3>.

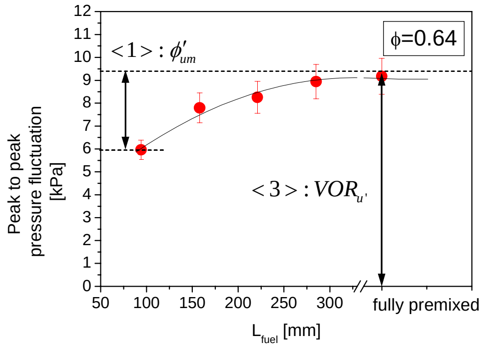


Fig. 10 Pressure fluctuations in partially premixed and choked fuel flow condition and fully premixed condition with mixing chamber (Ø=0.64)

4.3 Partially premixed and unchoked fuel flow modulated condition

4.3.1 Pressure fluctuations. Figure 11 compares the peak-to-peak pressure fluctuations, which we obtained under unchoked fuel flow modulated conditions by varying the L_{fuel} value when the equivalence ratio was constant at 0.64.

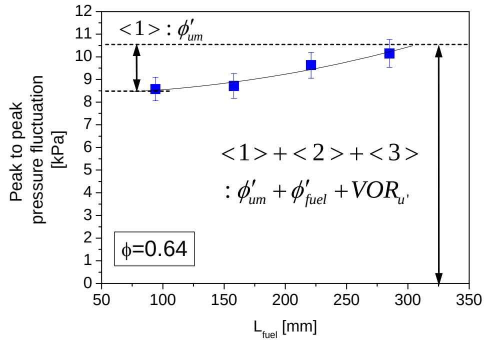


Fig. 11 Pressure fluctuations in partially premixed and unchoked fuel flow modulated condition (Ø = 0.64)

The pressure fluctuation decreased as the L_{fuel} value became smaller. We conclude, therefore, that the equivalence ratio fluctuation caused by the unmixedness of the fuel and air reduces the peak-to-peak pressure fluctuation. We also suggest, as shown in Fig. 11, that under these conditions the three causes of the pressure fluctuation should occur simultaneously when the mixing length is 285 mm.

Figure 12 compares the peak-to-peak pressure fluctuations, which we obtained under all conditions of this experiment by varying the L_{fuel} value when the equivalence ratio was constant at 0.64. Although we used the same amount of input fuel and air flow, we observed that the magnitude of the pressure fluctuation varied with each experimental condition. The periodic pressure fluctuation was due to the vortical motion of the mixture flow accounted for most of the total pressure fluctuation. That is, among the causes of the heat release rate fluctuation, the coherent vortex structures ($VOR_{u'}$) had a dominant effect on the pressure fluctuation of the combustion instability. We conclude therefore that the equivalence ratio fluctuation (ϕ'_{um}) that is due to the unmixedness of the fuel and air reduces the peak-to-peak pressure fluctuation under choked as well as unchoked conditions. Moreover, in Fig. 12, the hatched region between the two conditions indicates the equivalence ratio fluctuation (ϕ'_{fuel}) due to the fuel flow modulation.

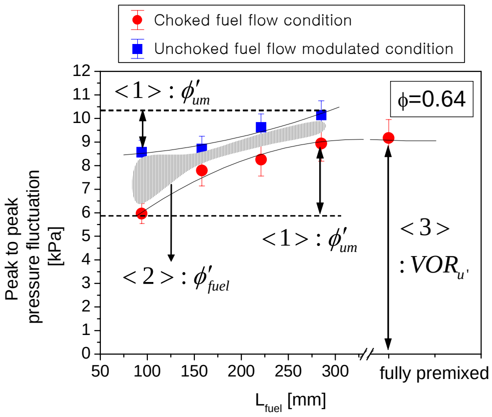


Fig. 12 Pressure fluctuations (Ø = 0.64)

5. Conclusion

To study combustion-driven instabilities, we used a dump combustor with LPG and air. We observed various types of pressure fluctuation with respect to the equivalence ratio and fuel injection condition. The combustion instability results from the thermoacoustic interaction and the instability mode is highly connected with the flame stabilization location. Followings are results of this study.

(1) We found that the causes of heat release rate fluctuation are not only equivalence ratio fluctuation due to the fuel and air flow modulation but also large vortical motion of the mixture flow and the unmixedness of the fuel and air.

(2) In the case of the same equivalence ratio, the equivalence ratio fluctuation that results from the unmixedness of the fuel and air reduces the peak-to-peak pressure fluctuation; in addition, the equivalence ratio fluctuation that is caused by the fuel and air flow modulation increases the peak-to-peak pressure fluctuation.

(3) Of all the factors that cause the heat release rate to fluctuate, the coherent vortex structures have the most dominant effect on the pressure fluctuations of the combustion instability.

(4) These results provide the combustion instability mechanism of the model gas turbine combustor and if these causes of combustion instability are properly considered they can help to design the more improved gas turbine combustors.

6. Acknowledgements

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