Characteristics of Unsteady Combustion and Combustion Control by Pulsating Mixture Supply

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ABSTRACT

The effects of unsteady combustion are experimentally studied using forced pulsating mixture supply. It was shown that unsteady combustion used in this experiment plays an important role in controlling self-excited combustion oscillations. It may also have desirable performances, from a practical point of view, such as high combustion load, augmented heat transfer, reduced pollutant emissions and so on. We examined the characteristics of unsteady combustion driven by forced pulsating mixture supply in a small duct-combustor with a rearward-facing step. Further, we found its influence on the onset of self-excited combustion oscillations, the possibility of suppressing self-excited combustion oscillations and the reason why the self-excited combustion oscillation was suppressed using the forced pulsating mixture supply, comparing with the steady mixture supply.

Keywords : unsteady combustion, combustion oscillation, pulsating mixture supply, oscillation control.

INTRODUCTION

The occurrence of combustion instabilities or oscillations often hinders improvement of performance in many practical combustors. It could lead to a catastrophic failure of the whole system, especially some of them are self-excited combustion oscillations caused by the feedback mechanism between fluctuations of pressure and heat release rate in a combustion chamber through mixture flow fluctuations. Rough combustion sometimes occurs when the acoustic mode of the combustor matches with the instability in the mixture flow, and it may cause undesirable results, such as mechanical vibrations or destruction of the system and intolerable combustion noise [1]. On the other hand, pulse-combustors that utilize self-excited oscillation of the system are well known as one of the effective combustion technologies to achieve high combustion load, augmented heat transfer and reduced pollutant emissions [2].

The geometry of the flow system, such as the volume of combustion chamber, the length of passages of reactants and exhaust gases, may yield countless modes of natural oscillation as the cause of combustion oscillation. Aerodynamic oscillations can be typically classified into either Helmholtz-type or longitudinal acoustic oscillation. Under a certain condition, if the fluctuation of heat release rate combines with one of the natural oscillation modes, self-excited combustion oscillation starts to occur by the resonance [3,4].

The control methods of self-excited combustion oscillation are divided into the passive control and the active control. The former is performed, for example, by changing the geometry of combustion devices, and the latter is achieved by the feed-back procedure in which the phase-sifted signals of pressure fluctuation of the combustion chamber are used to modify the feed rate of the mixture [5-10]. The onset of self-excited combustion oscillation requires that the relation between fluctuations in heat release rate and pressure in the combustor must satisfy the condition called Rayleigh' s criterion. Generally, the fluctuation of heat release rate and that of pressure have a phase difference. When the phase difference τ is in the range of $-\pi/2 < \tau < \pi/2$, it is known that Rayleigh' s criterion representing the onset of self-excited oscillation is satisfied.

In the present work, therefore, we studied the possibility of suppression of self-excited combustion oscillation by the pulsating mixture supply, which is forced by a reciprocating compressor. As a result, the self-excited combustion oscillation has been settled to some extent by the pulsating supply of the mixture, if the self-excited combustion oscillation was not strong enough. Moreover, these experiments revealed that the generation mechanism of self-excited combustion oscillation and the reason why the self-excited combustion oscillation was suppressed.

EXPERIMENTAL APPARATUS AND PROCEDURE

Figure 1 is a schematic drawing of the experimental apparatus used in the present study. The air flow rate was kept constant at 200 L/min or 180 L/min and the equivalence ratio of the premixed reactants was changed by regulating the flow rate of propane. Air was distributed to primary air that was mixed with fuel, and secondary air that was for the forced fluctuations. It is, therefore, possible to regulate the intensity of forced pulsating mixture supply. In order to assess the possibility of suppression of self-excited combustion oscillation, we examined two types of mixture supply. One was a steady-flow supply, that is, no forced flow modulation was added to the mixture flow during the study of self-excited combustion oscillation. The other was a pulsating mixture supply, i.e. forced fluctuations were introduced into the secondary air by a reciprocating-type compressor (Hitachi, 0.2 OP-5T). The reciprocating type compressor, bore and stroke of which were 50 mm and 18 mm, respectively, was used. The combustion rig consisted of three units; an approach section, a combustion chamber, and an exhaust duct. The inner cross section of the approach section was a rectangular of 40 mm x 25 mm

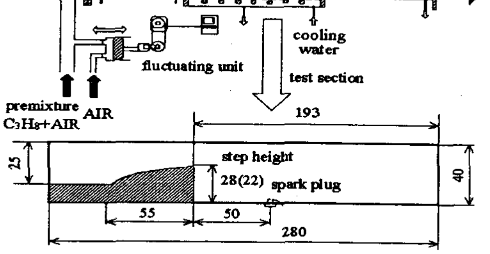


Fig.1 Experimental apparatus.

and 400 mm in length. The honeycomb-type flow straightener made of aluminum foil was inserted 300 mm upstream of the combustion section. The diameter of each cell of the honeycomb was 1/8 inch. In the experiment, two kinds of rearward-facing step were used; one is called "high-step" having height of 28 mm and a contraction rate of 48%, illustrated in Fig. 1, the other is "low-step" of 22 mm height and 72% contraction. Being contracted by the smoothly shaped surface of the rearward-facing step, the mixture flow is expanded suddenly into a square section of 40 mm x 40 mm. The mixture flow into the combustion chamber separates at the edge of rearward-facing step and forms a recirculating flow behind the step. At the start of operation, the mixture was ignited by a spark-plug placed 50 mm downstream from the rearward-facing step. The ceiling and bottom of combustion chamber was cooled by water. On each side of combustion chamber, a vycor glass plate of 300 mm x 55 mm and 3 mm thickness was installed to allow optical access. The actual observation area of the combustor was 280 mm x 40 mm. The inner cross section of the exhaust duct was 40 mm x 40 mm, and the total length of the duct can be adjusted by connecting the duct pieces of 150, 300, and 600 mm.

The instrumentation is shown in Fig. 2. In order to take two kinds of chemiluminescence images in the same combustion region with one unit of high-speed CCD camera (KODAK, EKTAPRO, HS Motion Analyzer) equipped with Imaging-Stereoscope (LaVision Inc.) was used. A pulse delay generator (Stanford Research System, WC Model DG535) was used to synchronize the high-speed CCD camera and an A/D converter (Elmec EC2390, sampling rate 50 kHz). A TTL signal generated by the pulse delay generator triggered the data acquisition on the high speed CCD camera for CH and OH chemiluminescence images and the A/D converter for signals of CH and OH chemiluminescence, pressure fluctuations in the combustion chamber and exhaust duct, respectively, and mixture flow rate. CH and OH chemiluminescence images were taken through an Imaging-Stereoscope equipped with an optical interference filter (OH : peak wavelength 308.5 nm, half width 18 nm, CH : peak wavelength 430.5 nm, half width 1.0 nm), a lens (Nikon, NIKKOR), and amplified by an image intensifier (Hamamatsu Photonics, C4412MOD), and then recorded by the high-speed CCD camera with the resolution of 256 pixel x 256 pixel in 8 bit. The acquired images were transferred to a personal computer (NEC, PC-9801ES). The semi-conductor pressure transducers (TOYODA, TYPE PMS-5) with a water cooled adapter and DC amplifiers (TOYODA, TYPE AA6200) were used for measuring pressure fluctuations in the combustion chamber and exhaust duct, respectively. The maximum response frequency of the semi-conductor pressure transducer was 10 kHz. The voltage signals from the semi-conductor pressure transducers were amplified by

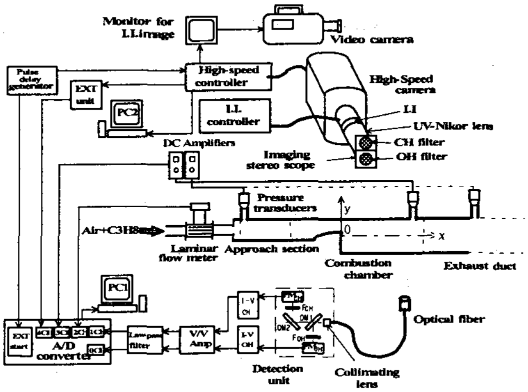
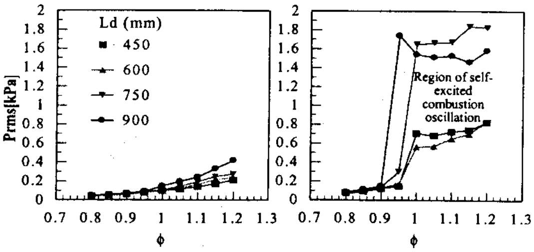


Fig. 2 Set-up of instrumentation.

a V/V amplifier and stored in the PC through the A/D converter. Pressure fluctuations were measured at the position 171 mm downstream of the rearward-facing step in the combustion chamber and every 150 mm on the exhaust duct.

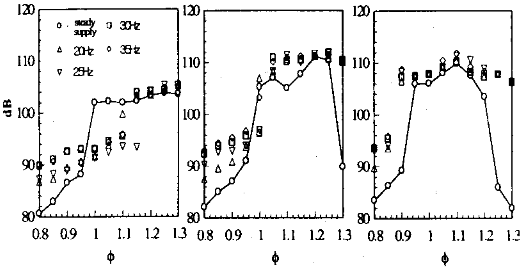
RESULTS AND DISCUSSION

The onset of combustion oscillation can be recognized by an abrupt increase in the far field sound level and in the pressure fluctuation intensity. Figure 3 shows an example for the change of RMS value of pressure fluctuations with the mixture equivalence ratio for the steady-flow mixture supply in case of air flow rate 200 L/min (mean Reynolds number, Re_m=6840), where Fig. 3(a) corresponds to the case of "low-step" and Fig. 3(b) "high-step". These results indicated that, in case of the steady-flow supply, self-excited combustion oscillations occurred only on the high-step within a range of the equivalence ratio. On the low step, in contrast, self-excited combustion oscillations did not occur for any duct length and any equivalence ratio. The influence of the forced pulsating mixture supply on the onset of self-excited combustion oscillation is shown in Fig. 4 for three sets of the duct length in case of air flow rate 200 L/min. The change of far field sound pressure level with the mixture equivalence ratio for the steady mixture supply is drawn by a solid line in each figure, while that for the forced pulsating mixture supply at the specified frequency is represented by each specific symbol. Some different tendencies for two kinds of mixture supply modes are observed in Fig. 4. For lean mixtures on which self-excited combustion oscillation did not occur for any duct length, the sound pressure level was slightly increased by the forced pulsating mixture supply. The reason is that the noise component generated by pulsating combustion is superimposed on the usual combustion noise. In case of a short duct of 450 mm, we found that self-excited combustion oscillation was suppressed even for the stoichiometric mixture by adding pulsation to the mixture supply. However, in case of a long duct of 900 mm, the pulsating mixture supply did not work satisfactory but produced higher noise level of about 110 dB, even slightly higher than that of self-excited combustion oscillation. Based on the experimental facts described above, we can say that the proposed forced pulsating mixture supply can suppress the onset of self-excited combustion oscillation unless the pressure fluctuations



(a) Low step (22mm) (b) High step (28mm)

Fig. 3 Variations of RMS value of pressure fluctuations for steady-flow mixture supply.



(a) L_d=450mm (b) L_d=600mm (c) L_d=900mm

Fig. 4 Influence of forced pulsating mixture supply on onset of self-excited combustion oscillation with the duct length L_d in case of the high step, where the duct length L_d is varied.

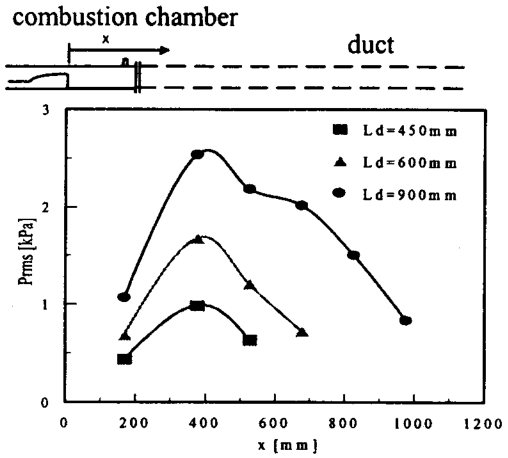


Fig. 5 Spatial distribution of the RMS of static pressure fluctuations for steady-flow mixture supply (High step).

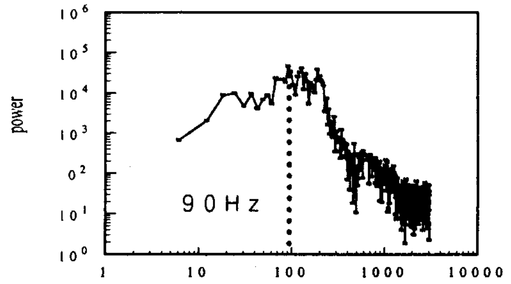


Fig. 6 Power spectrum of pressure fluctuation in case of the onset of self-excited combustion oscillation for steady-flow mixture supply (High step, L_d=600mm).

are so intense to be depressed, such as the case with a long duct. Figure 5 shows a typical example of the spatial distribution of RMS value of wall pressure fluctuations measured by the semi-conductor pressure transducers at combustion chamber and at every 150 mm on the exhaust duct when the self-excited combustion oscillation was occurred. For this condition, the air flow rate was kept at 180 L/min (mean Reynolds number, Re_m=6160, mixture equivalence ratio, ϕ=0.85). All cases show a half wave standing for the total length of the system, and almost coincide with a cosine curve. Hence, we can recognize that this system shows a longitudinal acoustic combustion oscillation with a standing wave when once it occurs.

Figure 6 shows an example of the power spectrum of pressure fluctuations in case of the self-excited combustion oscillation as shown in Fig 5. We can find three peaks existing between 90Hz and 180Hz anyone of which can resonate with any harmonic disturbance from outside, though the present peak frequency is about 90Hz.

Figure 7 shows the simultaneous time history of various quantities, when the self-excited combustion oscillation occurred; CH, OH chemiluminescence images, their band emission, pressure fluctuations in the combustion chamber and in the exhaust duct 150 mm upstream from the exit, respectively, and the pulsating flow rate of the mixture supply. The CH and OH chemiluminescence images seem to correspond to the heat release rate fluctuation of about 90Hz resulted from the unsteady recirculating vortex periodically formed downstream of the reward-facing step. Therefore, we consider that the peak frequency in this system is related to the vortex motion downstream of the reward-facing step. As shown in Fig. 7(a), the heat release rate begins to increase when the pressure in the combustion chamber approaches the minimum value, and then the mixture flow rate becomes its maximum value after pressure reaches the minimum. The heat release rate is increased due to augmentation of mixture flow rate. Hence, the expansion due to increased heat release rate produces a pressure rise. The trends observed are given in Fig. 7(b) and (c). The pressure comes to its maximum value with an elapsed time after the heat release rate reaches the peak intensity, as shown by Fig. 7(d), it is, therefore, considered that pressure fluctuation is caused by the fluctuation of heat release rate. While the pressure comes to the maximum, the amount of mixture brought into the combustion chamber decreases due to pressure rise, and thus combustion intensity becomes weak gradually and the pressure decreases again, as in Fig. 7(e) and (f). The pressure and signals of CH and OH intensity in the combustion chamber alters periodically, and the phase between pressure and signal of CH or OH intensity is almost coincided with each other. Even if there were a phase difference, it exists within the range of $-\pi/2<\varphi<\pi/2$, which indicates the condition of self-excited combustion oscillation. Moreover, there is almost no phase difference between pressures in the combustion chamber and in the duct, it is, therefore, confirmed that a standing wave is formed in the system when self-excited combustion oscillations occur.

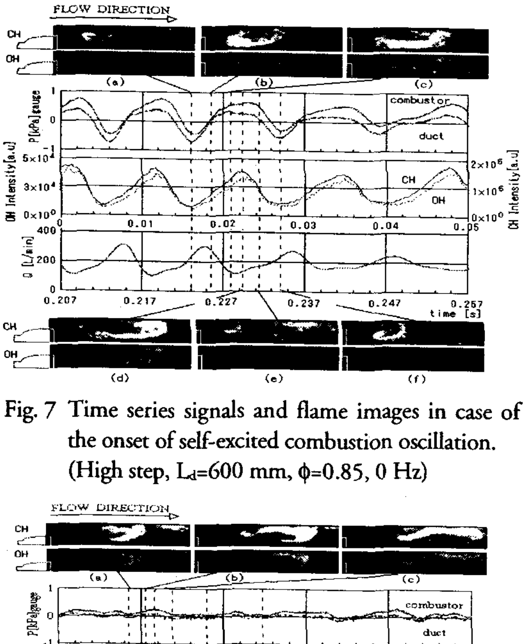


Fig. 7 Time series signals and flame images in case of the onset of self-excited combustion oscillation. (High step, L_d=600 mm, ϕ=0.85, 0 Hz)

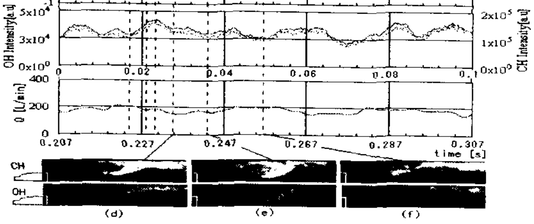


Fig. 8 Time series signals and flame images when the self-excited combustion oscillation is controlled using forced pulsating mixture supply. (High step, L_d=600 mm, ϕ=0.85, 30 Hz)

Figure 8 shows that the self-excited combustion oscillation can be controlled using a forced pulsating mixture supply of 30 Hz, when the self-excited combustion oscillation occurred without any forced pulsation. Although it is shown that the flame shape and location change continuously, as seen in CH and OH images, the periodicity corresponding to the forced 30 Hz was not always identified. We can conclude that the frequency of 30 Hz of forced pulsating mixture supply and that of 90 Hz of self-excited combustion oscillation were offset mutually. Accordingly, though we can see relatively small amplitude of the signals of CH and OH band emission and pressure fluctuation in the combustion chamber, any dominant periodicity was not found in them.

In spite of the forced pulsating mixture supply of 30 Hz, it generated only fluctuations of low amplitude in flow rate, hence in pressure. As a result, this lead to a conclusion that the periodic phenomena like a longitudinal acoustic combustion oscillation did not exist. The reason why self-excited combustion oscillation was suppressed using this small forced pulsation was that the unsteadiness of forced pulsating mixture supply distributed temporal heat release rate, which interfered with the pressure fluctuation and attenuated its amplitude which had been sustaining the self-excited combustion oscillation. However, it is difficult to control self-excited combustion oscillations using forced pulsating mixture supply if once strong oscillations are excited.

CONCLUSIONS

In order to investigate the characteristics of self-excited combustion oscillation, the influencing factors of its occurrence and the possibility of its control, experiments were carried out on combustion stabilized by a rearward-facing step, especially discussing differences between self-excited combustion oscillations and unsteady combustion using forced pulsating mixture supply. The obtained conclusions are as follows.

1. The peak frequency of the self-excited combustion oscillation dominating the system is in good agreement with the periodic motion of recirculating vortices formed in the wake of the rearward-facing step.
2. Self-excited combustion oscillation can be controlled using forced pulsating mixture supply as far as the intensity of pressure fluctuations of self-excited combustion oscillation is relatively weak.
3. It is difficult to control the self-excited combustion oscillation using forced pulsating mixture supply when once strong self-excited combustion oscillation occurred.
4. Generation mechanism of self-excited combustion oscillation has mutual relations with the rate of heat release, pressure fluctuation, and flow rate of mixture.

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