Characteristics of Self-excited Combustion Oscillation and Combustion Control by Forced Pulsating Mixture Supply

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Characteristics of self-excited combustion oscillation are experimentally studied using confined premixed flames stabilized by a rearward-facing step. A new idea to suppress combustion oscillation was applied to the flames. The characteristics of unsteady combustion were examined, which is driven by forced pulsating mixture supply that can modulate its amplitude and frequency. The self-excited combustion oscillation having weaker flow velocity fluctuation intensity than that of the forced pulsating supply can be suppressed by the method. The effects of the forced pulsation amplitude and frequency on controlling self-excited combustion oscillations were also investigated comparing with the steady mixture supply. The unsteady combustion used in this experiment plays an important role in controlling self-excited combustion oscillations, and it also exhibits desirable performances, from a practical point of view, such as high combustion load and reduced pollutant emissions of nitric oxide.

Key Words : Flame, Gaseous Fuel, Oscillating Combustion, Combustion, Premixed Combustion, Unsteady Combustion, Forced Pulsating Mixture Supply, Oscillation Control

1. Introduction

Premixed combustion has been noticed as an effective combustion method to increase combustion load and reduce nitric oxide emission. In case of adopting premixed combustion for practical combustors, however, the combustion instabilities or combustion oscillations often take place and hinder performance of combustors, for example, such as domestic boilers, a gas turbines, rocket engines, and so on. First, Putnum (1971) had explained the basic concept on self-excited combustion oscillation. Kishimoto (1995) studied the effects of self-excited combustion oscillation on domestic combustors.

Aerodynamic oscillations can be typically classified into either Helmholtz type or longitudinal acoustic oscillation. The geometry of flow system, such as volume of combustion chamber, length of passages of reactants and exhaust, may yield countless modes of natural oscillation as the cause of combustion 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. 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 as Rayleigh's criterion, expressed by the following relation,

$$E=\oint p'q'dt>0 \quad (1)$$

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where p' and q' are fluctuating component of pressure and heat release rate, respectively. 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 $-\pi/2<\tau/2$, it is known that the Rayleigh's criterion representing the onset of self-excited oscillation is satisfied. Control methods of self-excited combustion oscillation are divided into passive control and active control. The former is performed, for example, by changing the geometry of combustors, and the latter is achieved by feedback procedure in which the phase-shifted pressure fluctuation signals of the combustion chamber are used to modify the feed rate of the mixture. Katsuki (1986) studied the passive control, indicating that attempts to mitigate the intensity of oscillation by using various geometrical arrangements. Study of McManus (1993) is referred for the active control. It usually needs a high cost to perform the active control because of the complicated control system.

On the other hand, pulse combustors utilize combustion oscillation positively. Even though the basic generation mechanism of pulse combustion is the same as in combustion oscillation, it performs the intermittent combustion by connecting pressure fluctuation with intermittency of the flow rate. As a result, pulse combustion can be utilized as an effective combustion method to achieve high combustion load, reduced pollutant emission, especially, augmented heat transfer, which is attained by using high flow velocity fluctuations in the tail pipe. The pulse combustion, however, generates an intolerable combustion noise. Turbulent combustion is used mostly in practical combustors, but the mixture is supplied as a steady flow. Although many frequency components are contained in the turbulent spectrum of mixture flow, the combustion oscillation is occurred depending on rather the natural frequency of combustor system than the peak frequency of the spectrum of turbulent fluctuations. It is interesting to see how the onset of self-excited combustion oscillation is influenced by the resonance frequency of the flow system instead of the peak frequency in the turbulence spectrum contained in the mixture supply.

Present work, therefore, studied the effects of forced pulsating mixture supply performing continuous combustion in order to reduce the intolerable combustion noise of pulse combustion as well as to promote the merits of pulse combustor, such as high combustion load, reduced pollutant emission, augmented heat transfer, and so on. From this viewpoint, the combustion system using the characteristics of unsteady flow or forced pulsating mixture supply is hardly found in the past. The characteristics of combustion behavior was investigated in a duct-combustor with a rearward-facing step by applying unsteady combustion driven by a forced pulsating mixture supply of propane-air mixture. Further, it was confirmed that the forced pulsating mixture supply was useful to control the self-excited combustion oscillation by investigating its influence on the onset of self-excited combustion oscillations.

2. 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 147 L/min and the equivalence ratio of the mixture was changed by regulating the flow rate of propane. High-

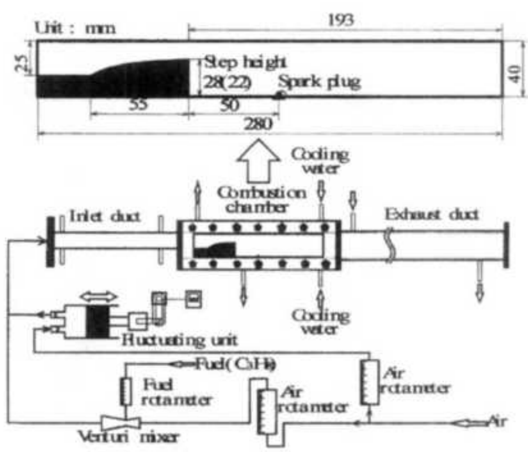


Fig. 1 Experimental apparatus

pressure air supplied from a compressor was distributed to primary air and secondary air, after dehumidifying through a dry filter. The primary air was mixed with fuel (propane) in a Venturi-mixer. Forced fluctuations were added to the secondary air by a reciprocating-type compressor (Hitachi, 0.2 OP-5T). The secondary air was mixed with the primary air, and mixture was supplied to the combustion chamber through an approach section with honeycomb-type flow straightener. As the result, in case of applying the forced pulsating mixture supply, although the equivalence ratio as well as the flow rate of mixture supplied to the combustion chamber is fluctuated, the time-mean value is always constant. The apparatus used for forced pulsating supply is driven by a D/C motor with a frequency variable inverter. The maximum pressure, bore and stroke of the reciprocating-type compressor were 0.5 MPa, 50 mm and 18 mm, respectively.

The combustion rig consists of three units, an approach section, a combustion chamber, and an exhaust duct. The mixture passes through the approach section with rectangular cross section of 40 mm×25 mm. Once contracted by the smoothly shaped surface of the rearward-facing step having height of 28 mm or 22 mm, the mixture flow is expanded suddenly into the combustion chamber with square section of 40 mm×40 mm. The flame is formed in a recirculating zone behind the rearward-facing step. On each side of combustion chamber, a vycor glass plate (width: 300 mm, height: 55 mm, thickness: 3 mm) was installed for optical access. Exhaust gas was released to the atmosphere through the exhaust duct located at downstream of the combustion chamber. The inner cross section of the exhaust duct was 40 mm× 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. The OH and CH chemiluminescence images from the flame, flow rate of the mixture, and pressure at two points in the combustion chamber can be measured simultaneously. In order to take two kinds of chemiluminescence images in the same combustion region with one high-speed CCD camera (Ektapro HS Model 4540, Kodak), an image-doubling mirror (Imaging-Stereoscope, La Vision Inc.) was used. CH and OH chemiluminescence images were taken by the high-speed CCD camera through 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) and a camera lens (UV Nikkor, Nikon) and amplified by an image intensifier (C4412MOD, Hamamatsu Photonics). Consecutive 1024 frames was recorded at frame rate of 4,500 per second. The fluctuation of flow rate of mixture supplied to the combustion chamber was

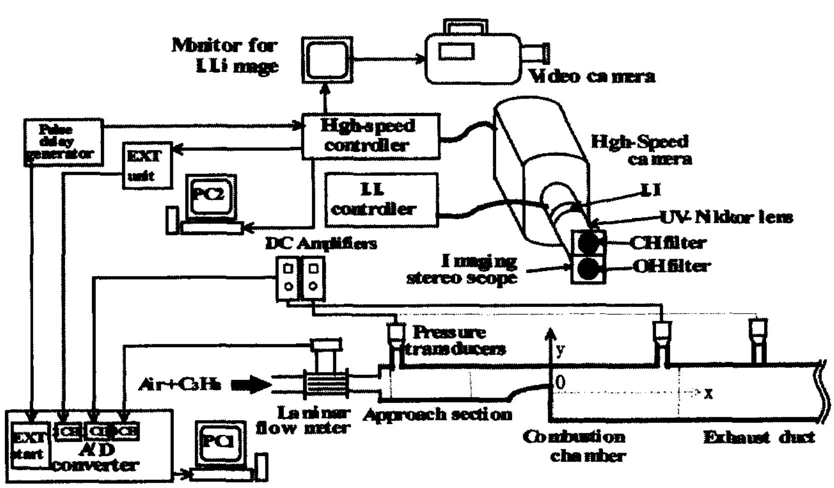


Fig. 2 Set-up of instrumentation

measured by laminar flow meter (Sokken, LFE-200LM) installed at 730 mm upstream from the rearward-facing step. The pressure difference from the laminar flow meter was converted into the voltage signal and recorded in the A/D converter with sampling rate of 50 kHz (DL2300LM, NEC Sanei Co., Ltd.).

The semi-conductor pressure transducers (Type PMS-5, Toyoda: maximum response frequency 10 kHz) with a water cooled adapter and DC amplifiers (Toyoda, Type AA6200) were used for measuring pressure fluctuations in the approach section, combustion chamber and exhaust duct, respectively. To prevent the distortion of the pressure signal caused by a connection pipe between the combustor and the semi-conductor pressure transducer, the connection pipe with a length of 40 mm and a diameter of 9 mm was used. Study of England and Richards (1984) was referred for deciding the length and diameter of connection pipe.

Pressure fluctuations were measured at 137 mm and 437 mm upstream of the rearward-facing step in the approach section, 171 mm downstream of rearward-facing step in the combustion chamber, and at every 150 mm in the exhaust duct. The voltage signals from the semi-conductor pressure transducers were amplified by a V/V amplifier and stored in the PC through the A/D converter. A pulse delay generator (WC Model DG535, Stanford Research Systems) was used to synchronize the high-speed CCD camera and the A/D converter.

Table 1 shows experimental conditions when the forced pulsation is supplied to the mixture. The total flow rate of primary air and secondary air was kept constant at 147 L/min (Mean Reynolds number, Re_m=5,030), and nondimensional fluctuation intensity ($FI=Q_{rms}/Q_{mean}$) of flow rate was changed by adjusting the ratio of the primary air to the secondary air. The frequency of the forced pulsation was changed by operating the inverter connected with reciprocating-type compressor at every 5 Hz from 15 Hz to 45 Hz. In the conditions of #1, #2 and #3, the frequency of the forced pulsation was kept as constant 30 Hz and the fluctuation intensity of flow rate was changed. In the conditions of #3, #4, #5 and #6, on the other hand, the fluctuation intensity of flow rate was almost constant (error estimate: $\pm 2\%$) and the frequency of the forced pulsation was changed. The case of supplying the mixture without the forced pulsation is defined as, "steady supply" and the case with forced pulsation is defined as, "pulsating mixture supply" in this study.

Table 1 Experimental conditions of forced pulsating flows

	#1	#2	#3	#4	#5	#6
Nondimensional Fluctuation Intensity, FI	0.30	0.22	0.19	0.20	0.20	0.19
Frequency, Hz	30	30	30	35	40	45

3. Results and Discussion

3.1 Characteristics of combustion oscillation in the case of steady flow

Figure 3 shows the RMS value of pressure fluctuation with respect to the mixture equivalence ratio in the case of steady supply with high rearward-facing step (28 mm). These results indicated that self-excited combustion oscillation, which is usually recognized by an abrupt increase in pressure fluctuation intensity, occurred only within a range of $\phi \geq 0.9$, $\phi \geq 0.8$ and $\phi \geq 0.75$, in case of the exhaust duct length of 450, 600, and

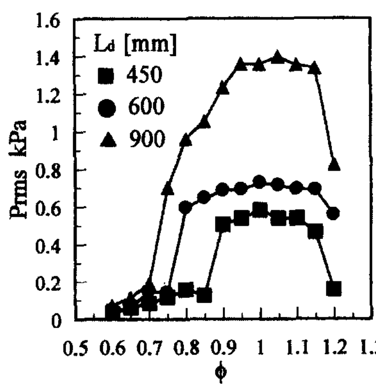


Fig. 3 Variations of RMS value of pressure fluctuations with respect to equivalence ratio in case of the high step

900 mm, respectively. As the exhaust duct length becomes longer, the self-excited combustion oscillation begins to occur at leaner equivalence ratio, and the pressure fluctuation becomes stronger.

As shown in equation (1), it is necessary to have positive correlation between the supply (or removal) of local energy and the pressure fluctuation for the pressure fluctuation in the system to be amplified spontaneously. That is, the fluctuating heat source (heat release rate) is indispensable to amplify the pressure fluctuation. Therefore, CH chemiluminescence, which is used as an index for representing the intensity of combustion reaction, and OH chemiluminescence, which represents the heat release rate of combustion reaction, the pressure fluctuation in the combustion chamber, and the fluctuation of flow rate of mixture were measured simultaneously and compared in two cases of combustion oscillation and no combustion oscillation. Many studies have been done to determine the instantaneous heat release and used the OH emission to represent the heat release from pulse combustors. The following reaction in hydrocarbon flames, $CH+O_2=OH^*+CO$, is probably the main route to the formation of OH in the excited state. The OH is proportional to the concentration of CH. The process of $^2\Sigma \rightarrow {}^2\Pi$ transition is occurred in about 1 μs, leading to the emission of ultraviolet radiation at about 307 nm. Therefore the intensity of this radiation is an indication of the heat release rate for the combustion. Studies of Mehta (1981), Keller (1987) and Richards (1998) are referred for OH chemiluminescence, and study of McManus (1990) is referred for CH chemiluminescence.

Figures 4 and 5 show the simultaneously monitored time-series data of CH and OH chemiluminescence images, pressure fluctuations in the combustion chamber, CH and OH chemiluminescence intensity emitted from the whole combustion chamber (summation of whole pixel intensity of CH and OH chemiluminescence images) and fluctuation of flow rate of mixture in cases of no self-excited combustion oscillation ($\phi=0.7$) and self-excited combustion oscillation ($\phi=0.8$), respectively.

In Fig. 4 with no combustion oscillation, though shape of OH and CH chemiluminescence images changes with time, CH and OH chemiluminescence intensity, which are considered to be in proportional to the heat release rate, emitted from the whole combustion chamber show weak fluctuation. Irregular fluctuations of high frequency are shown in the pressure in the combustion chamber and the flow rate of mixture. Even though this case is steady supply, it is considered that these results are due to interference of behavior of

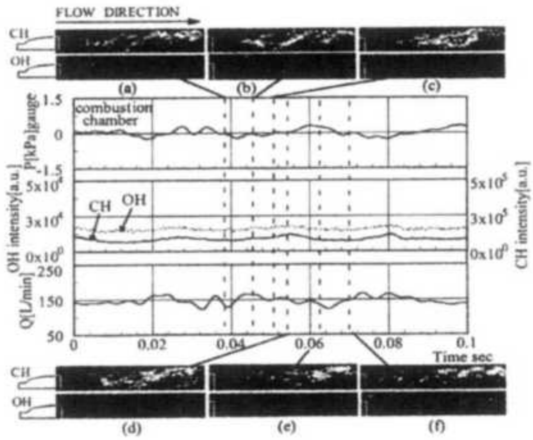


Fig. 4 Time series signals and flame images in case of steady combustion with the high step ($L_d=600$ mm, $\phi=0.7$)

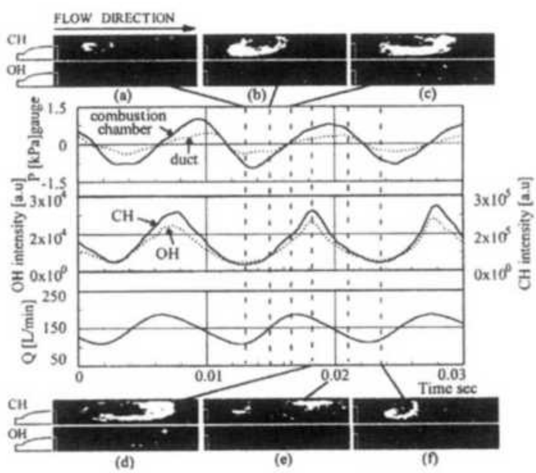


Fig. 5 Time series signals and flame images in case of self-excited combustion oscillation ($L_d=600$ mm, $\phi=0.8$)

turbulent shear layer exfoliated from the rearward-facing step and turbulent combustion. These are the general characteristics in turbulent combustion.

In case of the combustion oscillation as shown in Fig. 5, on the other hand, the regular periodicity is clearly observed in all signals. The bright portio of eddy-like shape in chemiluminescence image, which is considered to be the combustion reaction region, is fluctuated regularly. From these results, the self-excited combustion oscillation in the present system is considered to have relation with the movement of eddy-like shape combustion region formed downstream of the rearward-facing step.

As shown in the chemiluminescence image (a), though the eddy-like shape combustion region is small at the time of minimum pressure, the flow rate of mixture begins to increase just before the pressure become minimal. As flow rate of the mixture increases, intensity of OH and CH chemiluminescence increases gradually. The pressure increases according to the increase of OH and CH chemiluminescence intensity, the eddy-like shape combustion region becomes large, as shown in the chemiluminescence image (b) and (c). The chemiluminescence image (d) shows that the pressure becomes maximal after the heat release rate becomes maximal.

As the pressure increases, flow rate of the mixture reduces and consequently the heat release rate and the pressure decrease as shown in the chemiluminescence image (e) and (f), which is followed by the condition shown in the image (a). The pressure in the combustion chamber and OH and CH chemiluminescence from the whole combustion chamber are also periodic, and a phase difference, τ, exists within the range of $-\pi/2<\tau\pi/2$, which indicates the condition of self-excited combustion oscillation.

The power spectrum of pressure fluctuation in the combustion chamber was investigated to obtain the frequency of combustion oscillation while varying the equivalence ratio. The results are shown in Fig. 6. In the case of equivalence ratio of 0.7 with no combustion oscillation, though the peak spectrum of relatively high value can be seen at 46 Hz, feature of the whole shape of the spectra is like that in usual turbulent combustion.

The peak of frequency is appeared in the vicinity of 98 Hz when the self-excited combustion oscillation is just started ($\phi=0.8$), and the peak frequency becomes higher according to the increase of equivalence ratio. Although it is difficult to show all cases due to the limited space, the frequency of the combustion oscillation was found dominated by the standing wave of 3/4 wavelength mode according to the spatial distribution of rms value of the pressure fluctuations in terms of the total length of the system. That is, the node of the standing wave appeared slightly upstream of the rearward-facing step and the exit of the exhaust duct, while the antinode appeared at the combustion chamber.

The strongest oscillation for $\phi=1.0$ in the combustion chamber was dominated by the frequency of 122 Hz. Under this condition, it is observed that the dominant frequency at any location in the system, even though in the approaching section, was 122 Hz, which is the typical characteristic of the standing wave. Furthermore, the increase of the peak frequency with the increase of the equivalence ratio is understood that the equivalent length of exhaust duct becomes

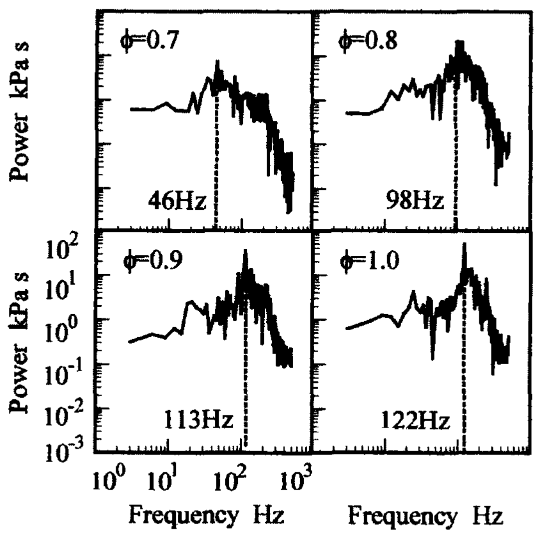


Fig. 6 Comparison of power spectra of pressure fluctuations when is changed from 0.7 to 1.0 at interval of 0.1 (L_d=600 mm)

shorter as the increase of exhaust gas temperature.

3.2 The control of combustion oscillation by the forced pulsating mixture supply

This section, based on characteristics of the self-excited combustion oscillation described above, examines the case that forced pulsating mixture supply is added to mixture when the self-excited combustion oscillation is occurred. The relations of rms value between the pressure fluctuation in the combustion chamber and the fluctuation of inflow velocity of the mixture are shown in Fig. 7 in order to investigate the influence of the strong pressure fluctuation caused by the combustion oscillation to the supply system. From these results, intensity of the pressure fluctuation in the combustion chamber is almost proportional to that of fluctuation of inflow velocity of the mixture, even though the slope is slightly different depending on length of the exhaust duct. The combustion oscillation doesn't occur in the region of left below the dotted line in Fig. 7, and both the pressure fluctuation in the combustion chamber and the fluctuation of inflow velocity of mixture are small.

Once the combustion oscillation occurs, on the other hand, strong fluctuation is abruptly appeared in the chamber pressure and the inflow velocity of mixture. Considering both results of Fig. 7 and the equation (1), there is a possibility for controlling the self-excited combustion oscillation by suppressing the pressure fluctuation directly or shifting phase of the fluctuation of heat release rate by intervening fluctuation of the inflow velocity of mixture. A method is considered here, shift phase of the fluctuation of the heat release rate by adding the forced pulsation with a frequency, which is different from that of the self-excited combustion oscillation.

Figure 8 shows comparison of rms value of the pressure fluctuation in the combustion chamber with and without the forced pulsating mixture supply shown in Table 1 in the condition that the self-excited combustion occurs in case of the steady supply. Figure 8(a) is the case that frequency of the forced pulsating mixture supply

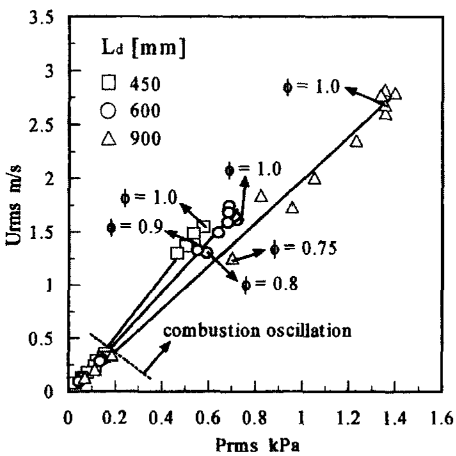
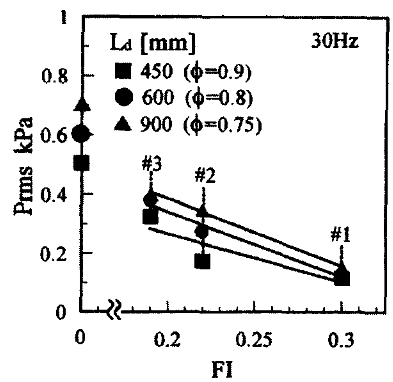
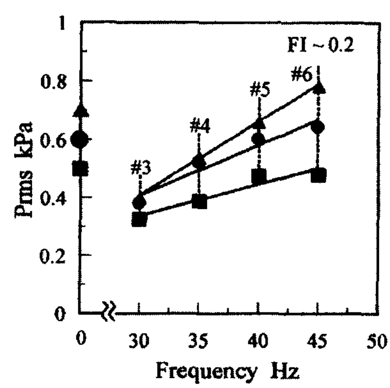


Fig. 7 Interrelations of RMS values of inlet velocity fluctuations of premixed mixture with RMS value of pressure fluctuations



(a) Effect of amplitude



(b) Effect of frequency

Fig. 8 Effects of forced pulsating mixture supply on combustion oscillation is kept constant at 30 Hz and the fluctuation intensity is changed by using the conditions of #1, #2 and #3 shown in table 1. Figure 8(b) is the case that fluctuation intensity is almost kept constant and the frequency of forced pulsating mixture supply is changed by using the conditions of #3, #4, #5 and #6.

Figure 8 (a) shows that the pressure fluctuation in the combustion chamber decreases as the fluctuation intensity of flow rate of mixture increases and rms value of pressure fluctuation shows lower values than that of steady supply, which corresponds to the condition of FI=0. In Fig. 8(b), although the rms value of pressure fluctuation increases as frequency of the forced pulsating mixture supply increases, the rms value is lower than that of the steady supply in case of the exhaust duct length L_d=450 mm. The rms value of pressure fluctuation is, however, higher than that of the steady supply above some frequency in case of the exhaust duct length L_d=600 and 900 mm. These results show that the self-excited combustion oscillation can be suppressed more effectively by supplying the large amplitude fluctuation than increasing frequency of the forced pulsating mixture supply.

The self-excited combustion oscillation is started in the case of L_d=600 mm and ϕ=0.8. However, the oscillation is suppressed by using the forced pulsating mixture supply condition #1 shown in Table 1. Figure 9 shows simultaneously monitored time-series data of CH and OH chemiluminescence images, pressure fluctuations in the combustion chamber and in the exhaust duct (450 mm downstream from the combustion chamber), CH and OH chemiluminescence intensity emitted from the whole combustion chamber, and fluctuation of flow rate of mixture in the suppressed condition.

From these images, it is found that location and shape of the combustion region changes irregularly and no periodicity corresponding to 30 Hz of the forced pulsating mixture supply is found in the pressure fluctuation. It is considered that the frequency of 30 Hz of the forced pulsating mixture supply and 98 Hz of the self-excited combustion oscillation are counterbalanced mutually. On the other hand, it is found that intensity of the chemiluminescence images and flow rate of the mixture fluctuate at about 30 Hz with small amplitude. This result shows that the phenomenon is dominated by the frequency of the forced pulsating mixture supply more than that of the self-excited combustion oscillation.

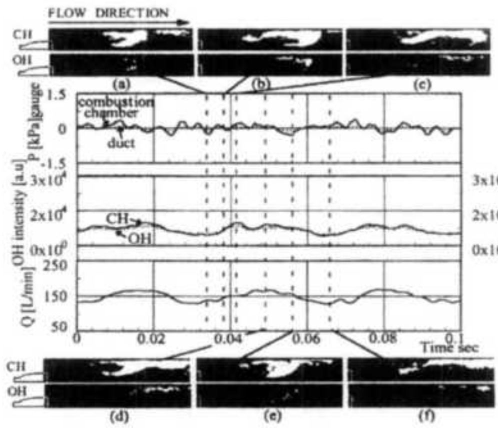
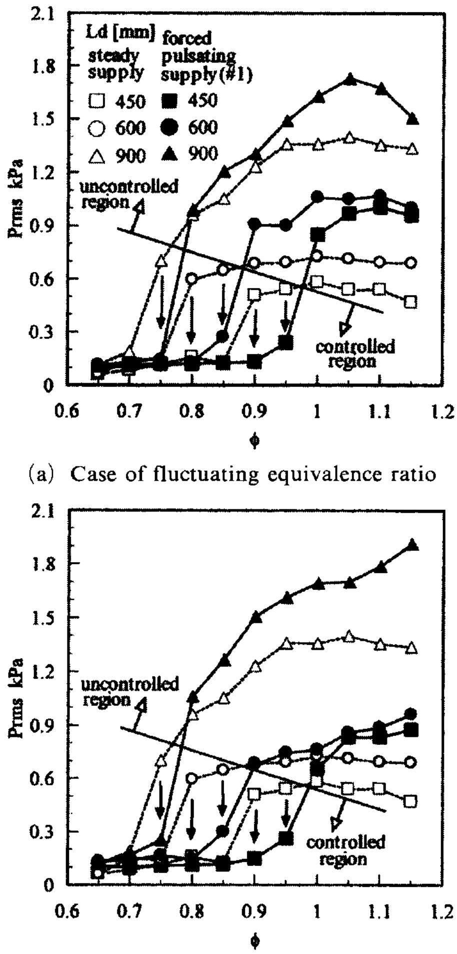


Fig. 9 Time series signals and flame images when self-excited combustion oscillation is controlled using forced pulsating mixture supply (supply condition : #1, L_d=600 mm, ϕ=0.8)

Although the intensity of chemiluminescence fluctuates, which corresponds to combustion reaction rate, the amplitude is very small and almost no periodicity is found comparing with the case of the combustion oscillation shown in Fig. 5. As a result, we can see that the pressure fluctuation becomes small and the periodic phenomena like a longitudinal acoustic combustion oscillation aren't observed. By observation of the fluctuation of flow rate of mixture, in spite of supplying the forced pulsating mixture supply of FI=0.3 at 30 Hz, the fluctuation of flow rate is very small. The reason why the self-excited combustion oscillation was suppressed using the forced pulsation was that the unsteadiness of the forced pulsating mixture supply attenuated the pressure fluctuation in the combustion chamber counterbalancing with the pressure fluctuation by the self-excited combustion oscillation.

As shown in Fig. 8, however, it is difficult to suppress the self-excited combustion oscillation using the forced pulsating mixture supply if once



(a) Case of fluctuating equivalence ratio

(b) Case of constant equivalence ratio

Fig. 10 Influences of forced pulsating supply (#1) on self-excited combustion oscillations with respect to equivalence ratio

strong oscillation is excited. That is, the forced pulsating mixture supply can not counterbalance the pressure fluctuation of the self-excited combustion oscillation.

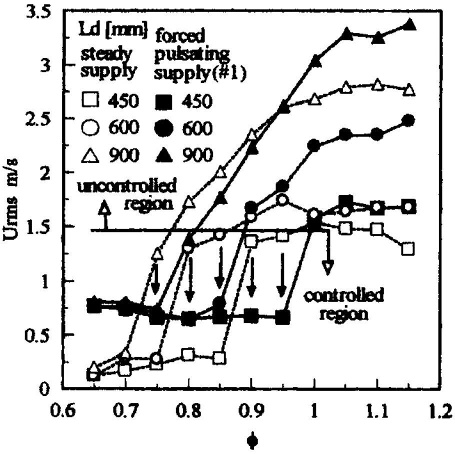
In Fig. 10, the rms value of pressure fluctuation due to combustion oscillation in the steady supply is compared with that of suppressed combustion oscillation by adding the #1 forced pulsating mixture supply, varying the equivalence ratio. In both cases of Figure 10(a) and (b), time mean values of equivalence ratio are the same. However, as explained in Fig. 1, Fig. 10(a) is the case where the equivalence ratio as well as the flow rate of mixture was modulated with the flow rate change. Figure 10(b), on the other hand, is the case that the equivalence ratio was always kept constant as the result of moving the Venturi-mixer upstream of the place where the air supply line is divided into the primary and secondary air.

In Fig. 10, the case of the steady supply is represented by white-key and that of the forced pulsating mixture supply is represented by black-key. In addition, the range where the combustion oscillation is suppressed by the forced pulsating mixture supply is indicated by an inclined solid boundary line. The conditions of the combustion oscillation, the white-keys located below the limit line, are changed into the black-keys representing no combustion oscillation by the forced pulsating mixture supply.

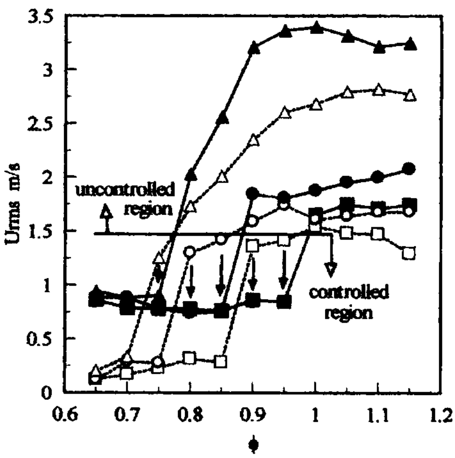
Comparing the Fig. 10(a) with 10(b), both the case (a), where both equivalence ratio and flow rate of the mixture are fluctuated, and the case (b), where equivalence ratio of the mixture is kept constant while flow rate is fluctuated, have almost the same range of the equivalence ratio where the combustion oscillation can be suppressed. From the results, it is found that the fluctuation of equivalence ratio has weaker influence than that of flow rate in controlling the combustion oscillation by forced pulsating mixture supply. However, it is difficult to conclude, at this moment, when the onset of combustion oscillation starts in terms of the rms value of the pressure fluctuations, because the controlled limit of combustion oscillation was changed with the equivalence ratio.

By changing the ordinate of Fig. 10, rms value of the pressure fluctuation in the combustion chamber, to that of velocity fluctuation of the mixture at the reward-facing step, Fig. 11 shows the similar results to Fig. 10. The controlled limit of combustion oscillation becomes the horizontal line that U_{rms} is about 1.5 m/s, and it is found that combustion oscillation within the range of $U_{rms}=1.2\times1.5$ m/s can be suppressed.

In case of the lean equivalence ratio where the combustion oscillation doesn't occur in the steady supply, although the combustion oscillation



(a) Case of fluctuating equivalence ratio



(b) Case of constant equivalence ratio

Fig. 11 Influences of forced pulsating supply (#1) on self-excited combustion with respect to equivalence ratio

doesn't occur by adding the forced pulsating mixture supply, the intensity of fluctuation of flow velocity is increased. This is because the forced pulsating mixture supply is overlapped on turbulent fluctuation in the steady supply. In equivalence ratio higher than the stoichiometry, the experiment is not performed because the residual fuel burns at the exit of the exhaust duct.

If the forced pulsating mixture supply of FI= 0.3 (experimental condition #1) is converted into the rms value of fluctuation of flow velocity while passing the rearward-facing step, it becomes about 1.5 m/s. Therefore, It could be concluded that the self-excited combustion oscillation is suppressed, if the intensity of fluctuation of flow velocity due to the self-excited combustion oscillation is smaller than that of the forced pulsating mixture supply. That is, the control of self-excited combustion oscillation can be attained only in the case where intensity of the self-excited combustion oscillation is weaker than that of the fluctuation of flow velocity with forced pulsating mixture supply. In addition, in case that U_{rms} is greater than about 1.5 m/s, the intensity of combustion oscillation is more increased due to adding the forced pulsating mixture supply.

3.3 The combustion of forced pulsating mixture supply under no combustion oscillation

Although the weak self-excited combustion oscillation could be suppressed using the forced pulsating mixture supply, the effect of the forced pulsating mixture supply on the combustion performance will be examined under the condition with no self-excited combustion oscillation in this section.

If height of the rearward-facing step is changed form 28 mm to 22 mm, the region of equivalence ratio where the abrupt increase in rms value of pressure fluctuation, shown in Fig. 3, is not observed. In case of the low step height, no abrupt increase in rms value of pressure fluctuation occurs in whole region of equivalence ratio at any exhaust duct length condition and that the rms value is very small with no self-excited combustion, as shown in Fig. 12. In addition, it is observed that because the recirculation zone formed downstream of the rearward-facing step is shortened in case of the low step (22 mm), length of the combustion region is elongated comparing with that of the high step (28 mm).

Figure 13 shows various time-series data obtained when the #1 forced pulsating mixture supply is added to the case of the low step, where the self-excited combustion oscillation occurred in case of the high step. Comparing to the result in Fig. 5, which corresponds to case of the high step, the result of Fig. 13 is close to that of Fig. 4

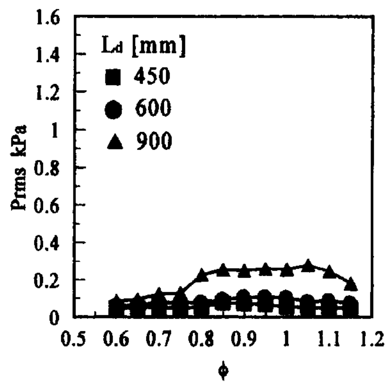


Fig. 12 Variations of RMS value of pressure fluctuations with respect to equivalence ratio in case of the low step

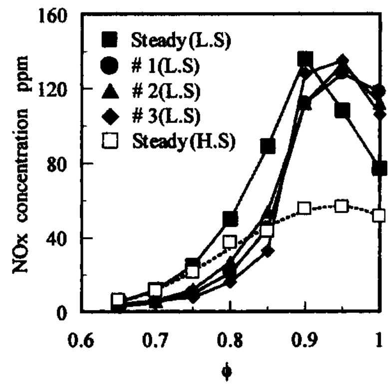


Fig. 14 Comparison of NOx concentration in the exhaust gas between steady and forced pulsating supply (#1~#3) (L_d=600 mm, H.S : High step, L.S ; Low step)

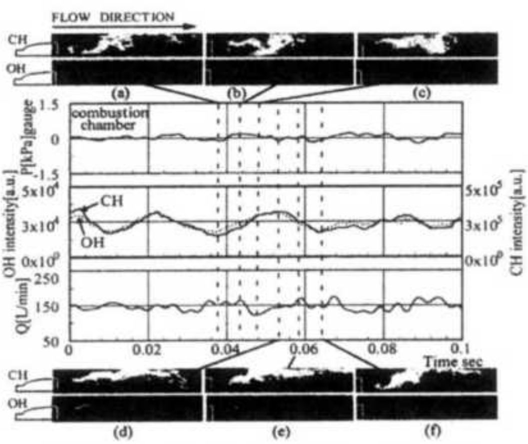


Fig. 13 Time series signals and flame images is case of steady combustion with the low step (L_d=600 mm, ϕ=0.8)

where the pressure fluctuation is small and the combustion oscillation doesn't occur. However, the shapes of OH and CH chemiluminescence images considerably change with time. In case of the high step, the flame accompanied with the large vortex movement of unsteady flow is formed in downstream of the rearward-facing step. In case of the low step, on the other hand, the flame close to the usual turbulent flame is stabilized by the step and moves periodically with fluttering by the forced pulsating mixture supply. As a result, length of the flame region becomes shorter com pared to that of the steady supply.

Figure 14 shows concentration of the nitric oxide emission measured at the exit of the exhaust duct under various conditions. Comparing with the two cases of the high and low step in the steady supply, although there is no difference in concentration of the nitric oxide emission because of no combustion oscillation in the range of $\phi<0.75$, concentration of the nitric oxide emission in case of the high step becomes lower than that of the low step because of the combustion oscillation in the range of $\phi>0.8$. This is because the nitric oxide emission is suppressed due to the effects like the pulse combustion. Study of Keller (1990) is referred for the mechanism of the nitric oxide emission in the pulse combustion. On the other hand, in case of the low step with adding the forced pulsation, concentration of nitric oxide emission in the range of $\phi<0.85$ (lean side of the stoichiometry) is much lower than that of the steady supply. Even though the combustion oscillation doesn't occur in the low step case, combustion with low peak temperature can be realized by mixing of unburned mixture and high-temperature product because the flame stabilized by the step moves periodically with fluttering by adding the forced pulsating mixture supply, as shown in Fig. 14. Hereby, it is considered that the thermal nitric oxide emission is reduced.

4. Conclusions

In order to investigate characteristics of the self-excited combustion oscillation, the influencing factors of the occurrence, and the possibility of the control, experiments were carried out on combustion stabilized by a rearward-facing step using forced pulsating mixture supply, which was different method from the conventional active control. The obtained conclusions are as follows.

(1) The self-excited combustion oscillation occurred in the present combustion system in the steady supply is dominated by the behaviors of circulation flow, that is, size is changed correlating with pressure fluctuations in the combustion chamber, and fluctuations of flow rate of mixture downstream of the rearward-facing step, and combustion. Moreover, the dominant frequency corresponds to the frequency of the standing wave with 3/4-wave length mode over the whole length of the system.

(2) The self-excited combustion oscillation can be suppressed effectively by the forced pulsating mixture supply as far as the intensity of the velocity fluctuations of self-excited combustion oscillation is weaker than that of forced pulsating mixture supply. By using this method, there is a possibility to control the onset of self-excited combustion oscillation. However, it is difficult to suppress the oscillation once a strong self-excited combustion oscillation has started.

(3) In the combustor operated with forced pulsating mixture supply but no self-excited combustion oscillation, nitric oxide emission can be reduced in some cases because combustion with low peak temperature can be realized as the result of large scale enhanced mixing of unburned mixture and high-temperature products by the added forced pulsating supply.

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