

# COMBUSTION CONTROL OF SELF-EXCITED COMBUSTION OSCILLATION AND NO<sub>x</sub> REDUCTION BY FORCED PULSATING MIXTURE SUPPLY

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**Abstract** : An idea to suppress the self-excited combustion oscillation was applied to confined premixed flames stabilized by a rearward-facing step. The characteristics of unsteady combustion driven by forced pulsating mixture supply that can modulate its amplitude and frequency were examined. The self-excited combustion oscillation having weaker flow velocity fluctuation intensity than that of the forced pulsating mixture supply can be suppressed by the method. The effects of the amplitude and frequency of forced pulsating mixture supply on controlling the self-excited combustion oscillations were also investigated comparing with the steady mixture supply. The unsteady combustion used in the present 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 NO<sub>x</sub>.

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**Key Words** : Flame, Combustion Oscillation, Combustion Control, Forced Pulsating Mixture Supply, NO<sub>x</sub>

## INTRODUCTION

Combustion instabilities occur due to many causes in practical combustors. In some cases, they lead to the self-excited combustion oscillation with strong pressure fluctuation that causes troublesome problems, for example, such as hindrance of combustor performance and intolerable combustion noise and so on.<sup>1-3)</sup> The self-excited combustion oscillation often occurs, for example, in some industrial boilers, gas turbines and rocket engines and so on.<sup>4-6)</sup> 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 pressure fluctuation and fluctuation of heat release rate in the combustor must satisfy the condition called as Rayleigh's criterion, which is expressed by the following relation.

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

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Here,  $p'$  and  $q'$  are fluctuating component of pressure and heat release rate, respectively. The

pressure fluctuation and fluctuation of heat release rate, generally, have a phase difference. When the phase difference  $\tau$  is in the range of  $-\pi/2 < \tau < \pi/2$ , 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 combustor,<sup>7-9)</sup> 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.<sup>10-12)</sup>

In order to elucidate the mechanism of self-excited combustion oscillation or utilize the merits of self-excited combustion oscillation positively, like pulse combustors, many studies have been conducted.<sup>13-21)</sup> Trying to reduce the pollutant emissions has been performed in various fields.<sup>22,23)</sup> Even though the basic generation mechanism of pulse combustion is the same as that of 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 and especially reduced pollutant emission. The pulse combustion, on the other hand, generates an intolerable combustion noise.

In order to reduce the intolerable combustion noise of pulse combustion as well as to promote the merit of pulse combustor, the effects of forced pulsating mixture supply performing continuous combustion were examined in the present study. 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 were 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 oscillation and reduce the NOx gas.

## EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental apparatus used in the present study is shown in Figure 1. The flow rate of air was kept constant at 147 L/min and the equivalence ratio of mixture was changed by regulating the flow rate of propane. The primary air was mixed with fuel (propane) in a Venturi mixer. Forced pulsating mixture supply was added to the secondary air by a reciprocating-type compressor (Hitachi, 0.2 OP-5T). In the 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 mixture supply is driven by a D/C motor with a frequency variable inverter.

The combustion rig consists of three units, an inlet duct, a combustion chamber, and an exhaust duct. The mixture passes through the inlet duct with rectangular cross section of 40 mm x 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 x 40

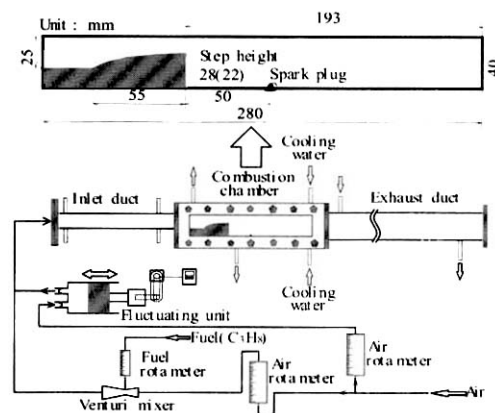


Figure 1. Experimental apparatus.



type compressor at every 5 Hz from 30 Hz to 45 Hz. In the conditions of #1, #2 and #3, the frequency of forced pulsating mixture supply 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 pulsating mixture supply was changed. The case of supplying the mixture without the operation of inverter is defined as “steady supply” and the case of supplying the mixture with the operation of inverter is defined as “unsteady supply” or “forced pulsating mixture supply” in this study.

## RESULTS AND DISCUSSION

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

Figure 3 shows the direct photographs of flame in the combustion chamber with high rearward-facing step (28 mm). Figure 3(a) is the case of steady combustion where the self-excited combustion oscillation does not occur ( $L_d = 600$  mm,  $\phi = 0.75$ ), and Figure 3(b) is the case where the self-excited combustion oscillation occurs ( $L_d = 600$  mm,  $\phi = 0.8$ ). Figure 3(c) is the case where the self-excited combustion oscillation is controlled by adding forced pulsating mixture supply (experimental condition #1 as shown in Table 1) to the case of Figure 3(b). In the case of the steady combustion, it is observed that the flame is usual turbulent flame stabilized by the rearward-facing step as the flame holder. In the case of self-excited combustion oscillation, the flame becomes shorter and wider compared with that of steady combustion. Further, the phenomenon of flashback, strong pressure fluctuation and intolerable combustion noise are observed. The flame of controlled the self-excited combustion oscillation by adding forced pulsating mixture supply is almost the same as that of steady combustion.

In this study, therefore, the reason why the

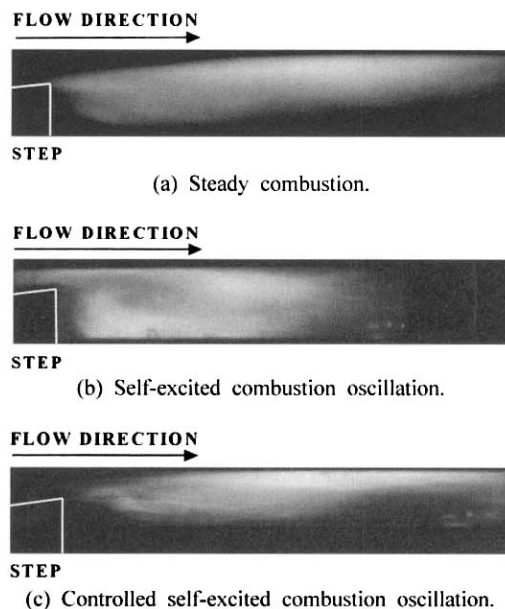


Figure 3. Comparison of flames in combustion chamber.

self-excited combustion oscillation is suppressed by adding forced pulsating mixture supply, as shown in Figure 3(c), will be investigated. For this purpose, the characteristics of self-excited combustion oscillation, as shown in Figure 3(b), are examined before investigating the possibility for controlling the self-excited combustion oscillation.

Figure 4 shows the rms value of pressure fluctuation with respect to the equivalence ratio of mixture in the case of steady supply with high rearward-facing step (28 mm). These results indicated that the self-excited combustion oscillation, which is usually recognized by an abrupt increase in an intensity of pressure fluctuation or far field sound pressure level, occurred only within a range of  $\phi \geq 0.9$ ,  $\phi \geq 0.8$  and  $\phi \geq 0.75$  in the case of the exhaust duct length of 450, 600, and 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. By considering the Rayleigh's criterion, it is necessary to have positive correlation between the supply (or removal) of local energy and the pressure fluctuation in the

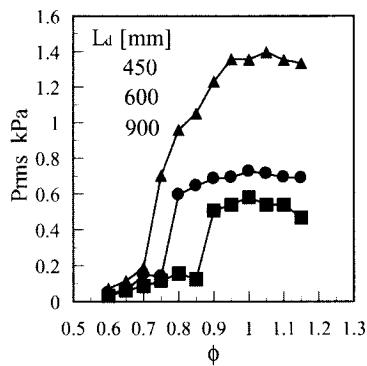


Figure 4. RMS values of pressure fluctuations with respect to equivalence ratio in the case of high rearward-facing step.

system to be amplified spontaneously. Edwards et al.<sup>25)</sup> and Segawa<sup>26)</sup> performed the numerical simulation to predict the pressure fluctuation when combustion instabilities and combustion oscillation occur, respectively. 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, or OH chemiluminescence, which represents the heat release rate of combustion reaction, and the pressure fluctuation in combustion chamber were measured simultaneously. Many studies have been done to determine the instantaneous heat release.<sup>27-30)</sup>

Figure 5 shows the spatial distributions of the rms of pressure fluctuation in terms of total length of the system in the cases of starting to occur the combustion oscillation and strong combustion oscillation, respectively. In this system, the node of pressure fluctuation is located in the vicinity of rearward-facing step ( $X = 0$  mm) and the anti-node is located in combustion chamber. Further, the exit of exhaust duct corresponds to the node of pressure fluctuation. It is observed that once the self-excited combustion oscillation starts to occur, its spatial distribution of the rms of pressure fluctuation has almost the same mode with that of strong combustion oscillation. By analysis of power spectrum of pressure fluctuation, it was observed that, if the self-excited combustion oscillation

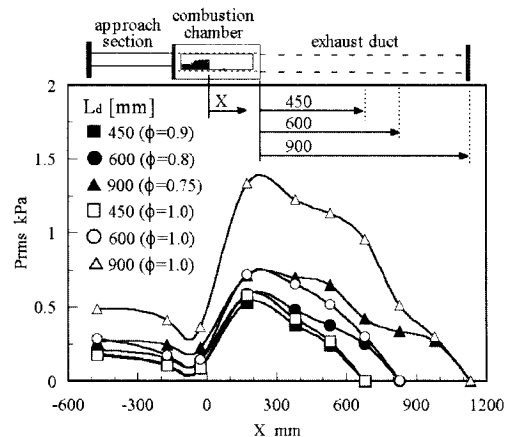


Figure 5. Spatial distribution of rms of pressure fluctuations in terms of total length of system.

occurred, the peak frequency in every location of combustor had the same value. The frequency of combustion oscillation was dominated by the standing wave of  $3/4$  wavelength mode. That is, the node of standing wave appeared slightly upstream of rearward-facing step and the exit of exhaust duct, while the antinode appeared in the combustion chamber. Further, it is found that, if the self-excited combustion oscillation occurs in the system, the effects of pressure fluctuation are also appeared in the upstream of inlet duct, in other words, the supply system, as well as in the combustion chamber. Especially, this phenomenon should be noticed in designing the combustors where the self-excited combustion oscillations are apt to occur.

Figure 6 and Figure 7 show the simultaneously monitored time-series data of CH and OH chemiluminescence images, pressure fluctuations in combustion chamber, CH and OH chemiluminescence intensities 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 the cases of no self-excited combustion oscillation ( $\phi = 0.7$ ) and self-excited combustion oscillation ( $\phi = 0.8$ ), respectively.

In Figure 6 with no combustion oscillation, even though the shape of OH and CH chemiluminescence images changes with time, CH and

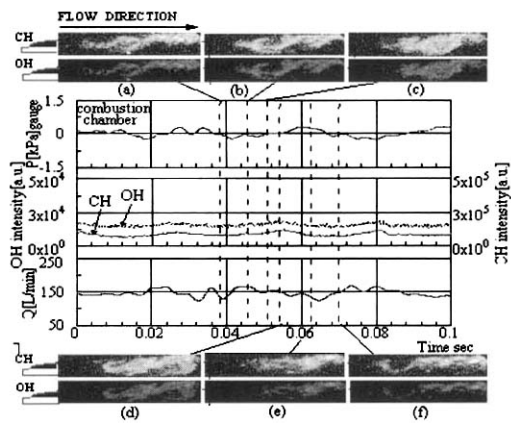


Figure 6. Time series signals and flame images in the case of steady combustion with the high rearward-facing step. ( $L_d = 600$  mm,  $\phi = 0.7$ )

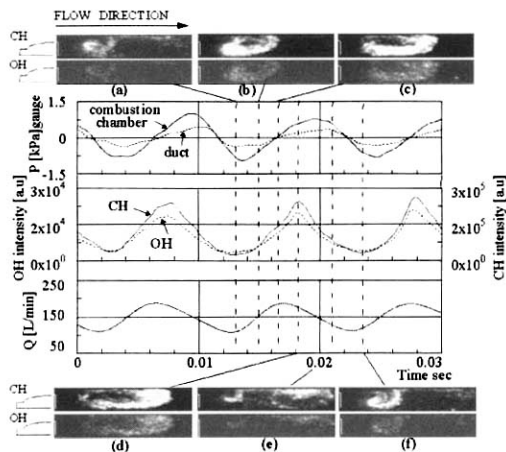


Figure 7. Time series signals and flame images in the case of self-excited combustion oscillation. ( $L_d = 600$  mm,  $\phi = 0.8$ )

OH chemiluminescence intensities, 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 observed in the pressure fluctuation and the flow rate of mixture. Even though this is the case of steady supply, it is considered that these results are due to interference of behavior of turbulent shear layer exfoliated from the rearward-facing step and turbulent combustion. These are the general characteristics in turbulent combustion.

In the case of the self-excited combustion

oscillation as shown in Figure 7, on the other hand, the regular periodicity is clearly observed in all signals. Eddy-like shape bright portion 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. It was observed that, the peak frequency was the 98 Hz by analyzing the power spectrum of pressure fluctuation, as observing from the time-series signal of pressure fluctuation in Figure 7.

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 larger, 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 combustion chamber and OH and CH chemiluminescence from the whole combustion chamber are also periodic, and a phase difference,  $\tau$ , exists within the range of  $-\pi/2 < \tau < \pi/2$ , which indicates the condition of self-excited combustion oscillation.

The rms values of the pressure fluctuation in combustion chamber with and without the forced pulsating mixture supply shown in Table 1 are shown in Figure 8, when the self-excited combustion occurs in the case of the steady supply.

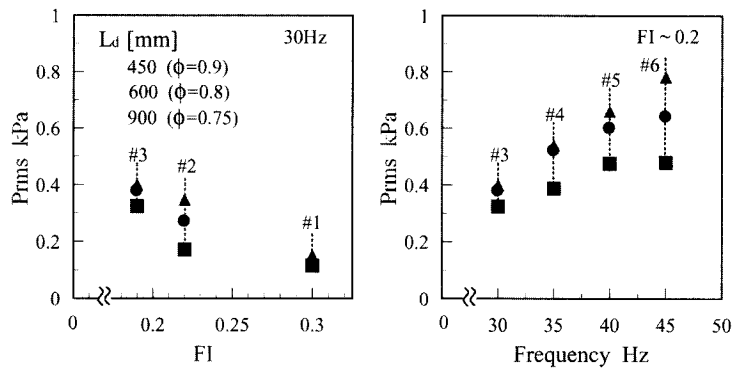


Figure 8. Effects of forced pulsating mixture supply on combustion oscillation.

Figure 8(a) is the case that frequency of the forced pulsating mixture supply 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 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 Figure 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 the case of the exhaust duct length  $L_d = 450$  mm. The rms value of pressure fluctuation is, on the other hand, higher than that of the steady supply above some frequency in the 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 rms values of pressure fluctuation due to the self-excited combustion oscillation in steady supply are compared with that of suppressed self-excited combustion oscillation by adding the forced pulsating mixture supply (#1) in Figure 9.

In both cases of Figure 9(a) and (b), the time-mean values of equivalence ratio are the same. However, as explained in Figure 1, Figure 9(a) is the case where the equivalence ratio as well as the flow rate of mixture was modulated with the flow rate change. Figure 9(b) is, on the other hand, the case that the equivalence ratio was always kept constant, as the result of moving the Venturi-mixer to upstream of the place where the air supply line is divided into the primary and secondary air.

The case of steady supply is represented by white-key, and the case of the forced pulsating mixture supply is represented by black-key in Figure 9. The range where the combustion oscillation is suppressed by forced pulsating mixture supply is indicated by an inclined solid boundary line. The conditions of 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 Figure 9(a) with 9(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.

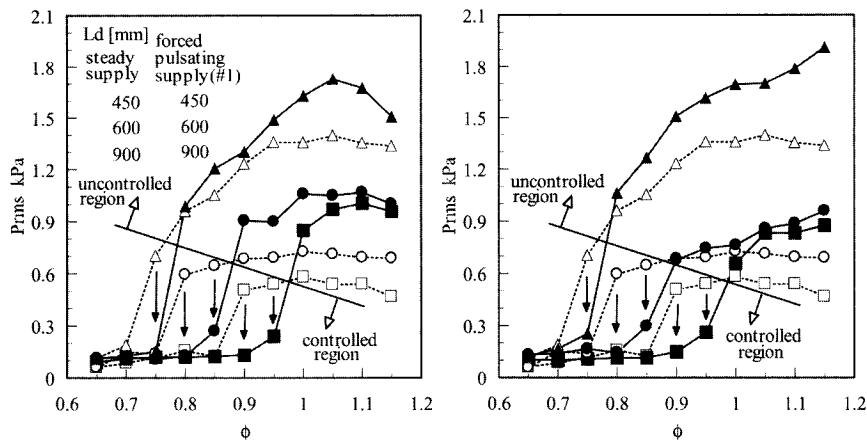


Figure 9. Influences of forced pulsating supply (#1) on self-excited combustion oscillations with respect to equivalence ratio.

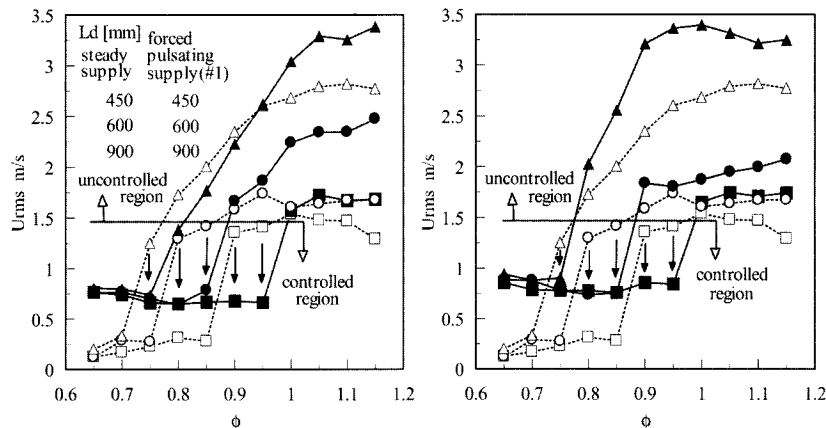


Figure 10. Influences of forced pulsating supply (#1) on self-excited combustion with respect to equivalence ratio.

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 Figure 9, rms value of the pressure fluctuation in combustion chamber, to that of velocity fluctuation of the mixture at the rearward-facing step, Figure 10 shows the similar results to Figure 9. The controlled limit of combustion oscillation becomes the horizontal line that  $U_{rms}$  is about 1.5 m/sec, and it is found that combustion oscillation within the range of  $U_{rms} = 1.2(1.5$  m/sec can be

suppressed.

Although the combustion oscillation doesn't occur by adding the forced pulsating mixture supply, the intensity of fluctuation of flow velocity is increased in condition of the lean equivalence ratio where the combustion oscillation doesn't occur in steady supply. This is because the forced pulsating mixture supply is overlapped on turbulent fluctuation in 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/sec. 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 the intensity of self-excited combustion oscillation is weaker than that of the fluctuation of flow velocity with forced pulsating mixture supply. In addition, the intensity of combustion oscillation is more increased due to adding the forced pulsating mixture supply in the case that  $U_{rms}$  is greater than about 1.5 m/sec.

### Reduction of NOx by Forced Pulsating Mixture Supply

In this section, in order to reduce the NOx by using the forced pulsating mixture supply, the effects of forced pulsating mixture supply in condition of no self-excited combustion oscillation will be investigated. If the height of the rearward-facing step is changed from 28 mm (high step) to 22 mm (low step), the self-excited combustion oscillation doesn't occur in whole region of equivalence ratio at any exhaust duct length. It has relation to the passive control, that is, controlling the self-excited combustion oscillation by changing the geometry of combustor. By resulting the rms value of pressure fluctuation in the case of low step, its maximal value was about 0.2 kPa in condition of the exhaust duct length  $L_d = 900$  mm and equivalence ratio  $\phi = 1.0$ , even though this condition was the most strong self-excited combustion oscillation in the case of high step as shown in Figure 4. Therefore, it was observed that the flame was the usual turbulent flame stabilized by the rearward-facing step in all cases of low step.

The concentration of the NOx emission measured at the exit of exhaust duct under various conditions is shown in Figure 11. Comparing with two cases of the low step and the high

step in steady supply, although there is no difference in concentration of the NOx emission because of no combustion oscillation in the range of  $\phi < 0.75$ , the concentration of the NOx emission in the 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 NOx emission is suppressed due to the effects like the pulse combustion, as pointed out by the experiments of Keller et al.<sup>31)</sup> On the other hand, the concentration of NOx emission in the range of  $\phi < 0.85$  (lean side of the stoichiometry) is much lower than that of the steady supply in the case of the low step with adding the forced pulsating mixture supply. Even though the combustion oscillation doesn't occur in the case of the low step, the combustion with low peak temperature can be realized by mixing of unburned mixture and high-temperature product because the flame stabilized by rearward-facing step moves periodically with fluttering by adding the forced pulsating mixture supply. Although the amplitude of forced pulsating mixture supply is changed, the remarkable differences between concentrations of NOx emission in the cases of adding forced pulsating mixture supply are not observed.

In order to investigate the cause of reduction for concentration of NOx emission, the mean and rms values of temperature in the case of the

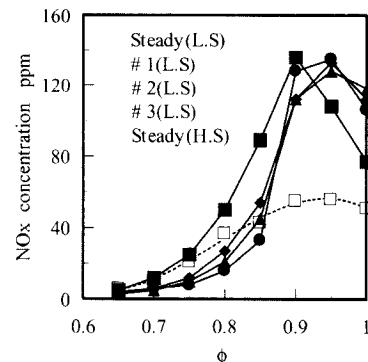


Figure 11. Comparison of NOx concentration in the exhaust gas between steady and forced pulsating supply (#1~#3). ( $L_d = 600$  mm, H.S.: High step, L.S.: Low step)

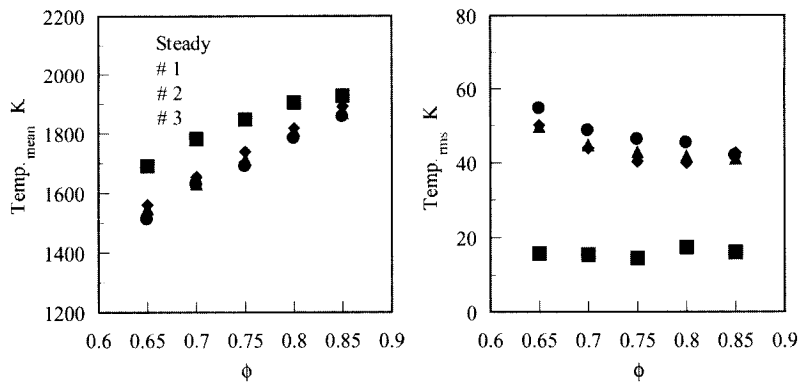


Figure 12. Comparison of temperature in the case of steady supply and forced pulsating mixture supply (#1 ~ #3). (Low step,  $L_d=600$  mm)

low step are shown in Figure 12. Temperature was measured using a Pt/Pt-13%Rh thermocouple of  $100 \mu\text{m}$  wire in diameter and measurement point was located at  $X = 130$  mm downstream from the rearward-facing step in combustion chamber. Temperature measurement was not performed in the condition where the equivalence ratio is more than 0.9 because of cut off of the thermocouple due to high temperature.

The mean temperatures in the cases of the steady supply and forced pulsating mixture supply are increased with increasing the equivalence ratio. Even though the mean and rms values of temperature between the forced pulsating mixture supplies (#1 ~ #3) show similar values, they show a different tendency compared with that of steady supply. That is, the values of forced pulsating mixture supply have lower mean temperature and larger rms value of temperature than those of steady supply. Further, the rms values of temperature are decreased with increasing the equivalence ratio. It is considered that, because the heat release rate and mean temperature become lower with approaching to lean combustion, they are apt to be influenced easily by the forced pulsating mixture supply.

Figure 13 shows CH chemiluminescence images and mean temperature distributions in the combustion chamber in the case of the low step

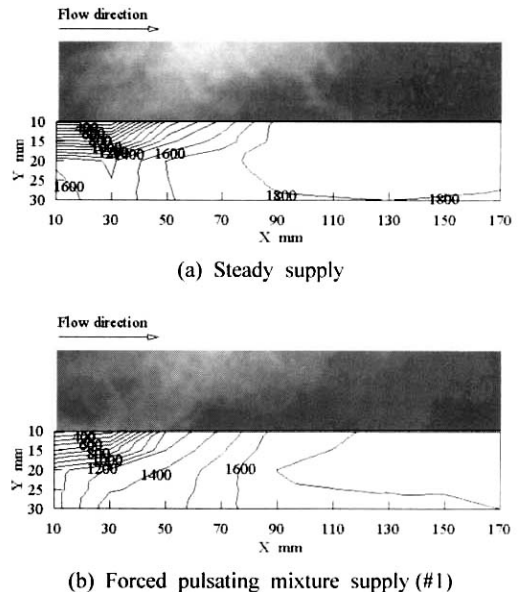


Figure 13. Comparison of CH chemiluminescence images and spatial temperature distributions (Low step,  $L_d = 600$  mm,  $\phi = 0.8$ ).

( $L_d = 600$  mm,  $\phi = 0.8$ ). CH chemiluminescence images of Figure 13(a) and (b) are the time-mean values of CH chemiluminescence images of 11 frames, which are taken at interval of 0.1 second. By comparing CH chemiluminescence intensities of the 2 conditions, the image of steady supply shows high intensity compared with that of the forced pulsating mixture supply. In the mean temperature distribution, the region of high temperature higher than 1800 K appears

in the downstream of combustion chamber in the case of the steady supply. However, the region of high temperature shows about 1,700 K in the case of forced pulsating mixture supply. That is, it is observed that, if the forced pulsating mixture supply is added, the high temperature in combustion chamber becomes lower by approximately 100~200 K compared with that of steady supply. Therefore, as shown in Figure 11, the reduction for concentration of NOx emission is caused by the fact that the region of high temperature higher than 1800 K disappears by the enhanced mixing of unburned mixture and high-temperature product due to the forced pulsating mixture supply.

## CONCLUSIONS

The influencing factors of the occurrence and the possibility on controlling the self-excited combustion oscillation were investigated. The experiments were carried out on confined premixed flames stabilized by a rearward-facing step using forced pulsating mixture supply, which was different method from the conventional active control. The obtained concluding remarks are summarized as follows.

1. In the case of the steady supply, the self-excited combustion oscillation is dominated by the behaviors of circulation flow, that is, the size is changed correlating with pressure fluctuations in combustion chamber, fluctuations of flow rate of mixture and combustion. 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. As far as the intensity of the velocity fluctuation of self-excited combustion oscillation is weaker than that of forced pulsating mixture supply, the self-excited combustion oscillation can be suppressed effectively by the forced pulsating mixture supply. Moreover, 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.
3. In the combustor operated with forced pulsating mixture supply in the case of no self-excited combustion, the NOx emission can be reduced in some cases because combustion with low peak temperature can be realized as the result of enhanced mixing of unburned mixture and high-temperature products by adding the forced pulsating mixture supply.

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