KSME International Journal, Vol. 18 No. 10, pp. 1859~1868, 2004

Symptoms of Self-excited Combustion Oscillation and their Detection

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Monitoring of OH chemiluminescence through an optical fiber was demonstrated to be a useful method in detecting self-excited combustion oscillations. OH chemiluminescence intensity detected by the optical fiber showed mostly excellent agreement with those obtained by high speed CCD camera measurements when combustion oscillations were strong. Symptoms of self-excited combustion oscillation were also studied in order to predict the onset of combustion oscillation before it proceeded to a catastrophic failure. For the purpose, we have found and proposed unique measures to tell the onset of self-excited combustion oscillations based on the careful statistics of fluctuating properties in flames, such as pressure or emission of OH radicals.

Key Words: Flame, Combustion Oscillation, Unsteady Combustion, Premixed Combustion, Oscillation Control, Symptom of Combustion Oscillation, Detection.

1. Introduction

Combustion instabilities occur due to many causes in 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. In the previous study, Yang et al. (2003) studied the characteristics of self-excited combustion oscillation using a duct-combustor with rearward-facing step when propane-air premixture was supplied to combustion chamber as a steady flow. We demonstrated that the forced pulsating mixture supply as a new control method for controlling self-excited combustion oscillation was effective by investigating the influences and characteristics on the onset of self-excited combustion oscillation. 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 performed.

Studies of Dec et al. (1989), Ichiro et al. (1993), Poppe et al. (1998), Yoon et al. (2002) and Kim et al. (2003) were referred for the merits of pulse combustion. In these studies, the most important measurement quantities to understand the behavior of combustion oscillation were the correlation between pressure fluctuation and fluctuation of heat release rate. As for the pressure fluctuation, it is measured in many cases using pressure sensor connected to combustion cham-

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ber, directly or through a connection pipe. However, it should be careful about the distortion of pressure signal within a connection pipe as indicated in studies of Englund et al. (1984) and Richards et al. (1998). As for the fluctuation of heat release rate, on the other hand, it is difficult to measure directly. Therefore, Richards et al. (1998) and Keller et al. (1987) used OH radical chemiluminescence and McManus et al. (1990) used CH radical chemiluminescence as an indicator of heat release rate.

In order to measure the chemiluminescence intensity exactly in time-series, it is necessary to count the summation of all pixel intensity of high-speed images of chemiluminescence emitted from whole combustion chamber. For the purpose, an optical window that covers whole region of combustion chamber is needed. However, this is not practical. Therefore, an optical fiber with a solid angle that covers whole region of combustion chamber is installed on the sidewall of combustion chamber, and fluctuations of chemiluminescence intensity are measured through the optical fiber. However, the chemiluminescence intensity measured through the optical fiber is not verified whether or not the values correspond to those obtained from the summation of all pixel intensity of chemiluminescence images taken by using high speed CCD camera, and can be used as a signal that indicates the fluctuation of heat release rate.

In the present study, in order to check the validity, the time-series data of summation of all pixel intensity of chemiluminescence images obtained by using high speed CCD are compared with those of chemiluminescence intensity measured through an optical fiber, which is very simple and low cost. Most of conventional methods for controlling the combustion oscillation focused on control after the occurrence of combustion oscillation. However, controlling after occurring strong combustion oscillation becomes more difficult, and this can't be a fundamental solution for controlling combustion oscillation. That is, if symptoms on the onset of combustion oscillation are detected by any techniques, the combustion oscillation can be controlled more effectively before it proceeds to a catastrophic failure. Even though various controlling methods have been proposed so far, the studies that are trying to detect the symptoms of combustion oscillation experimentally are hardly found.

In the previous study, the main purpose was the combustion control by using forced pulsating mixture supply when the self-excited combustion oscillation occurred. The result showed that the self-excited combustion oscillation could be suppressed effectively by forced pulsating mixture supply as far as the intensity of the velocity fluctuation of self-excited combustion oscillation was weaker than that of forced pulsating mixture supply. However, this method was for control after the combustion oscillation had started. Therefore, it is necessary to control before the onset of combustion oscillation. Even though, in the previous study, we found that the self-excited combustion oscillation was occurred abruptly while the equivalence ratio was changed within a small interval of 0.05 (from $\phi=0.75$ to 0.8 in case of $L_d=600$mm), but the transient phenomena during the interval of 0.05 were not examined completely. Therefore, this study tried to detect the symptoms of self-excited combustion oscillation by observing in detail the transient phenomena. For this purpose, the equivalence ratio was changed with very small interval of 0.01 during the transient process.

2. Experimental Apparatus and Procedure

The experimental apparatus used in this study is shown in Fig. 1. The arrangement of experimental apparatus was almost the same as that of previous study except that the equivalence ratio of mixture could be regulated at interval of 0.01. For this purpose, two rotameters (maximal flow rate : 15 L/min and 1 L/min) were arranged in parallel, and equivalence ratio was regulated precisely at interval of 0.01 by using rotameter with maximal flow rate of 1 L/min. Experimental condition was that the total flow rate of primary air and secondary air was kept constant at 147 L/min and the equivalence ratio of mixture was changed by regulating flow rate of propane, as shown in previous study

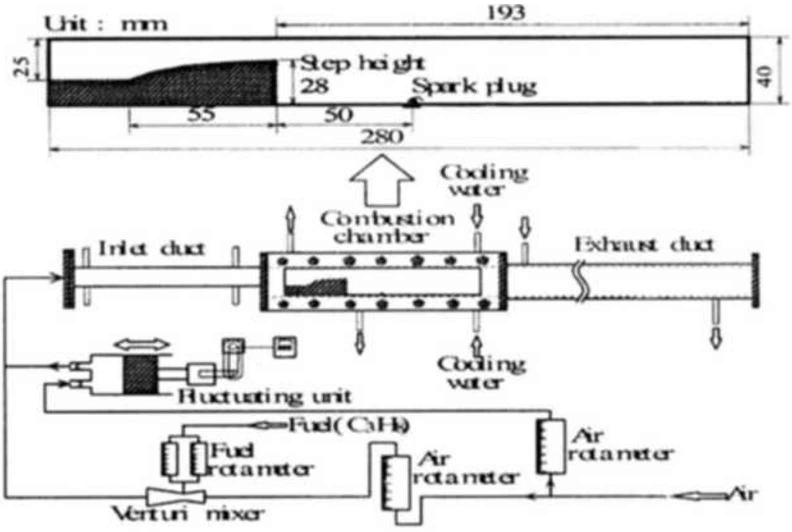


Fig. 1 Experimental apparatus

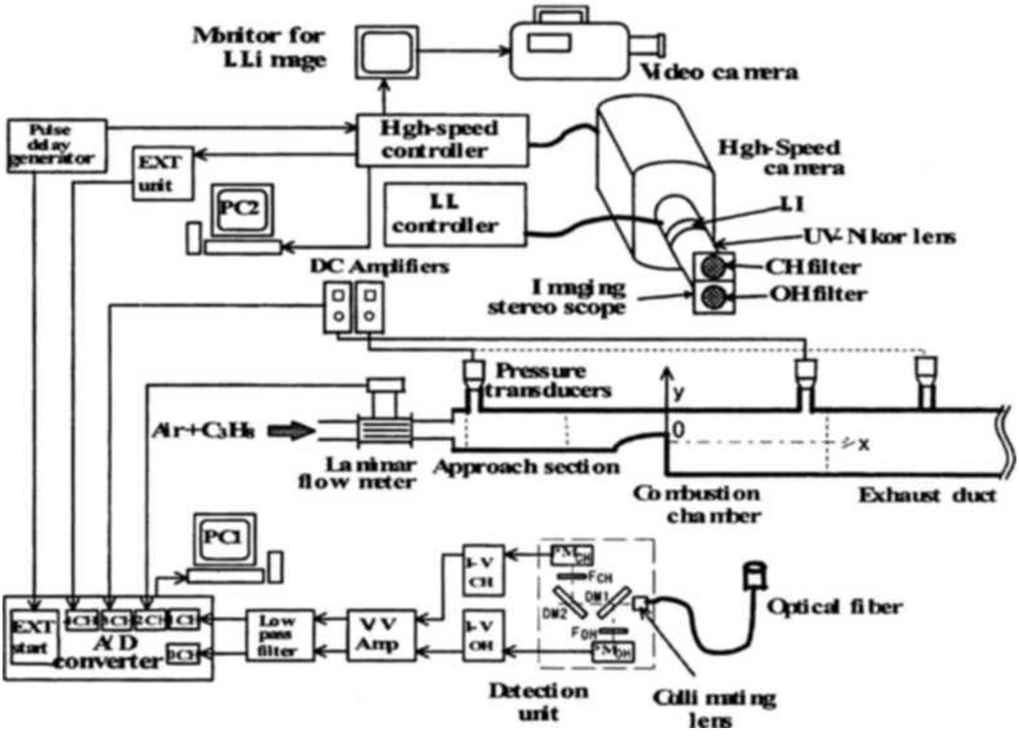


Fig. 2 Set-up of instrumentation

Figure 2 presents the instrumentation set-up. It is the same as that of previous study except for measurement system for chemiluminescence emitted from whole combustion chamber by using an optical fiber. In order to measure OH and CH chemiluminescence emitted from whole combustion chamber, the optical fiber was set to cover the area of whole combustion chamber, and a plate with hole of rectangular shape was used to protect a light emitted from outside of combustion chamber. OH and CH chemiluminescence emitted from whole combustion chamber was collected by ultraviolet-light-transmitted optical fiber (Mitsubishi Co. Ltd., STU1000H, NA=0.2, Core diameter=1mm), and detected separately by each photomultiplier (Hamamatsu Photonics, R106UH) after passing through optical components of collimating lens, dichroic mirrors and interference filters. Output current signal from each photomultiplier was converted into voltage signal by an I/V converter (NF Electronic Instruments, Model LI-76). After being amplified by a V/V amplifier and eliminating higher frequency components than 5kHz using a programmable filter (NF Electronic, FV-665), the voltage signal was stored in a PC through an A/D converter (DL2300LM, NEC Sanei Co., Ltd. Sampling rate: 50kHz). In this measurement system, OH and CH chemiluminescence images obtained by high speed CCD camera, OH and CH chemiluminescence collected by optical fiber, fluctuation of flow rate of premixture measured by laminar flow meter, and pressure fluctuations in combustion chamber and exhaust duct measured by semiconductor pressure transducers can be measured simultaneously in time-series.

3. Results and Discussion

3.1 Measurement of chemiluminescence using an optical fiber

In order to detect the combustion instabilities and the generation of self-excited combustion oscillation, chemiluminescence measurements using optical fiber have been frequently performed in many researches. From a view point of an optical measurement, it is also interesting to compare chemiluminescence intensity obtained as summation of all pixel intensity of chemiluminescence images taken by high speed CCD camera with chemiluminescence intensity collected by using optical fiber, which has merits as simple and low cost experimental apparatus. Furthermore, if there is a strong correlation between pressure fluctuation measured by pressure transducer and fluctuation of chemiluminescence intensity measured by optical fiber, the combustion oscillation can be evaluated by measuring only one of the two.

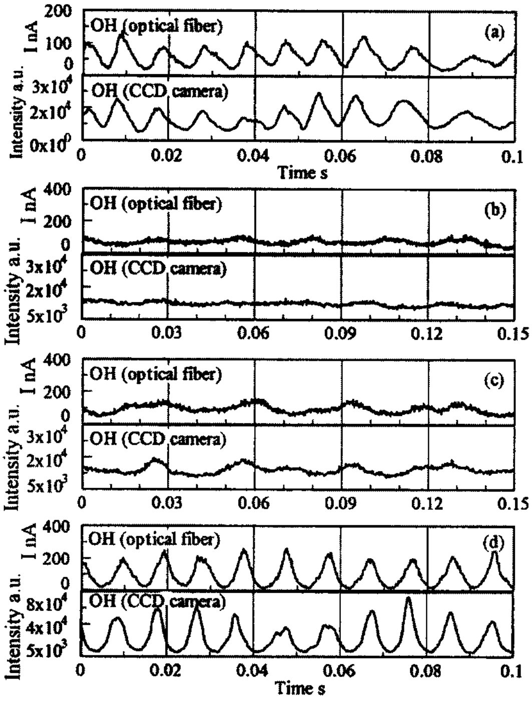


Fig. 3 Signals obtained by optical fiber and CCD camera, (a) Combustion oscillation with constant mixture supply, L_d=600mm, ϕ=0.8, (b) No oscillation with constant mixture supply, L_d=900mm, ϕ=0.7, (c) No oscillation suppressed with forced oscillating mixture supply, L_d=900mm, ϕ=0.75, (d) Intense combustion oscillation with constant mixture supply, L_d=900mm, ϕ=1.0.

Figure 3 shows simultaneously time-series signals of chemiluminescence intensity obtained as summation of all pixel intensity of chemiluminescence images taken by high speed CCD camera and chemiluminescence intensity collected by using optical fiber. Figure 3(a) shows that combustion oscillation begins to occur (ϕ=0.8) in case of duct length L_d=600mm and steady supply. All cases of Figs. 3(b), 3(c) and 3(d) are L_d=900mm, Fig. 3(b) is case of no combustion oscillation (ϕ=0.7) in steady supply, Fig. 3(c) is case of controlled combustion oscillation by adding forced pulsating mixture supply (experimental condition #1 in the previous study) after

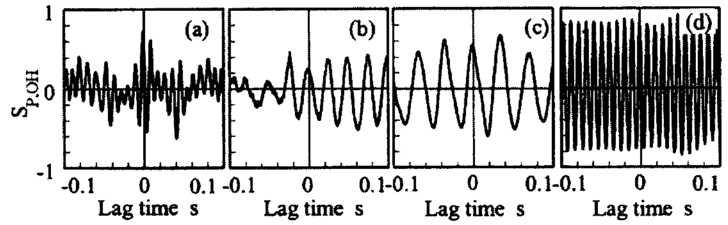


Fig. 4 Cross-correlation coefficient between optical fiber and CCD camera, (a) Combustion oscillation with constant mixture supply, L_d=600mm, ϕ=0.8, (b) No oscillation with constant mixture supply, L_d=900mm, ϕ=0.7, (c) No oscillation suppressed with forced oscillating mixture supply, L_d=900mm, ϕ=0.75, (d) Intense combustion oscillation with constant mixture supply, L_d=900mm,ϕ=1.0.

occurring the combustion oscillation (ϕ=0.75), and Fig. 3(d) is case of occurring the strongest combustion oscillation (ϕ=1.0) in steady supply. From these results, it is found that, in all cases of combustion oscillation, there is strong correlation between chemiluminescence intensity obtained as summation of all pixel intensity of chemiluminescence images and chemiluminescence intensity collected by optical fiber.

However, because we can't evaluate the correlation between the two quantities quantitatively by only showing their time-series data, the cross-correlation coefficient between the two quantities are shown in Fig. 4. Focusing on the maximal value of cross-correlation coefficient, it is 0.94 in case of Fig. 4(d) where the strong combustion oscillation occurs, 0.74 in case of Fig. 4(a) where combustion oscillation begins to occur, 0.67 in case of Fig. 4(c) where combustion oscillation is controlled by adding forced pulsating mixture supply, and 0.45 in case of Fig. 4(b) where no combustion oscillation occurs, respectively. These results show that maximal values of cross-correlation coefficient between two quantities become higher in case where combustion oscillation occurs and forced pulsating mixture supply is added. Particularly, the cross-correlation coefficient shows high values ranging from 0.74 to 0.94 in case where combustion oscillation starts and strong combustion oscillation occurs. It is found that, as the combustion oscillation becomes stronger, high correlation can be seen between chemiluminescence intensity obtained as summation of all pixel intensity of chemiluminescence images obtained by high speed CCD camera and chemiluminescence intensity collected by optical fiber.

Therefore, it is possible to evaluate the combustion oscillation by measuring chemiluminescence by using only optical fiber without using expensive high speed CCD camera, and we can say that the stronger the combustion oscillation is, the higher the reliability of measuring technique is.

3.2 Symptoms on the onset of self-excited combustion oscillation

If symptoms on the onset of self-excited combustion oscillation could be detected by any techniques, it would be more effective in its control. Figure 5 shows the maximal values of cross-correlation coefficient between OH (or CH) chemiluminescence intensity collected by optical fiber and pressure fluctuation in combustion

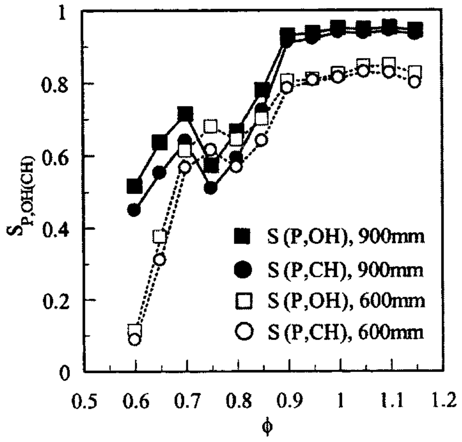
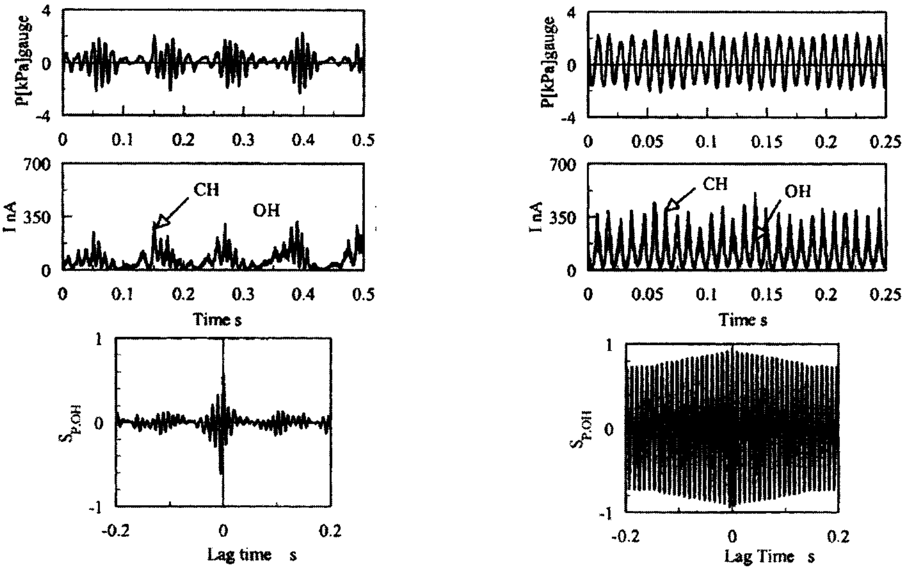


Fig. 5 Variation of cross-correlation coefficient between pressure and OH, CH.



(a) ϕ=0.75

(b) ϕ=1.0

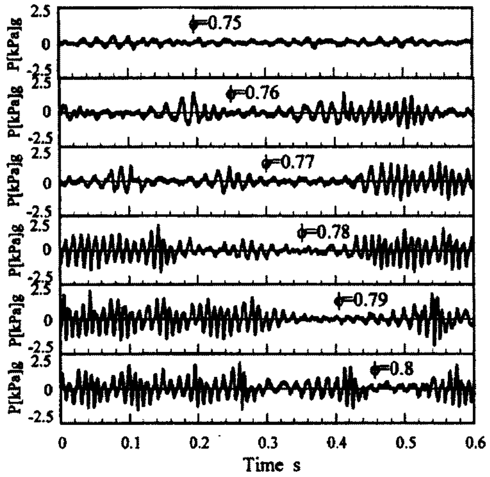
Fig. 6 Pressure and OH, CH-band signals and cross-correlation coefficients

chamber in functions of equivalence ratio. The maximal values of cross-correlation coefficient in case of L_d=900mm, where the strongest combustion oscillation occurs in this study, have high values comparing with those in case of L_d=600mm. This means that the stronger the intensities of combustion oscillation become, the higher the correlation between pressure fluctuation and fluctuation of heat release rate is. In case of L_d=900mm and 600mm, the maximal values of cross-correlation coefficient decreases and take minimal values at ϕ=0.75 and 0.8, respectively. By observing these results in detail, we can see that the equivalence ratio in which maximal values of cross-correlation coefficient take minimal values corresponds to the condition where combustion oscillation begins to occur. Moreover, the degree of decrease in maximal values of cross-correlation coefficient in case of L_d=900mm is larger than that in case of L_d=600mm. These results indicate that what the maximal values of cross-correlation coefficient between pressure and chemiluminescence intensity are abruptly dropped when combustion oscillation begins to occur is one of symptoms on the onset of combustion oscillation. We will discuss this cause later in detail.

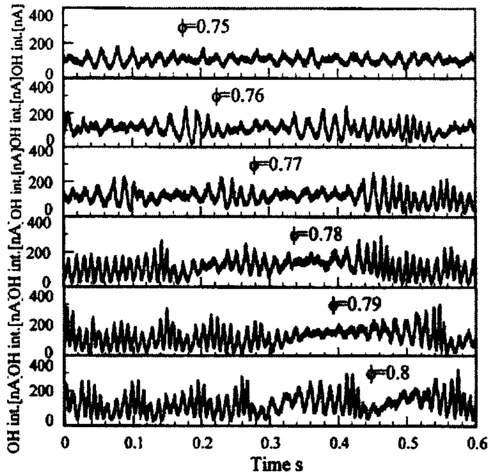
In cases of L_d=900 and 600mm, high correlations between pressure and chemiluminescence intensity are observed when equivalence ratio is larger than 0.9. Especially, in case of L_d=900mm, it is considered that combustion oscillation can be evaluated by measuring only one quantity of pressure or chemiluminescence intensity, because cross-correlation coefficient is very high (greater than 0.95) in case where equivalence ratio is near stoichiometry. In other words, if an ignition plug united with an optical fiber for measuring chemiluminescence intensity attached on sidewall of combustion chamber, the plug plays a role as a sensor for combustion oscillation.

In order to investigate the reason why the maximal values of cross-correlation coefficient between pressure and chemiluminescence intensity are abruptly dropped when combustion oscillation begins to occur, the time-series data and the cross-correlation coefficient between the two quantities are shown in Figs. 6(a) and (b) (in case of L_d=900mm). Fig. 6(a) shows the results that the maximal value of cross-correlation coefficient has the lowest value at equivalence ratio of 0.75 (combustion oscillation begins to occur), and Fig. 6(b) shows the results at equivalence ratio of 1.0 (the strongest combustion oscillation occurs). In Fig. 6(b), the periodic fluctuations are observed in two signals. However, we can see in Fig. 6(a) that two different phenomena in which pressure and chemiluminescence intensity are fluctuating with high correlation or low correlation alternately. That is, the pressure and chemiluminescence intensity are fluctuated with a certain phase difference during combustion oscillation, and high cross-correlation coefficient is obtained at a lag time corresponding to the phase difference. However, in unstable phenomenon in which the combustion oscillation occurred or stopped alternately, the pressure and chemiluminescence intensity are not fluctuated with a certain constant phase difference due to the influence of high heat release rate after occurring the combustion oscillation, as shown in Fig. 7(b). This is considered the reason why the cross-correlation coefficients are dropped when combustion oscillation begins to occur.

In order to detect the symptoms on the onset of combustion oscillation, we investigated carefully the transient process leading to combustion oscillation by gradually increasing the equivalence ratio at interval of 0.01. Figure 7(a) and (b) show simultaneously monitored time-series data of pressure and chemiluminescence intensity, respectively, in case of L_d=600mm. The equivalence ratio was gradually increased from 0.75 (no combustion oscillation) to 0.8 (onset of combustion oscillation) at interval of 0.01. From these results, the fluctuations of pressure and chemiluminescence intensity are increased gradually as the equivalence ratio is increased. In OH chemiluminescence signal at equivalence ratio of 0.77, the small fluctuations that indicate no combustion oscillation are observed after occurring the large fluctuations that indicate strong combustion oscillation. The average value of OH chemiluminescence intensity at equivalence ratio of 0.77 is high comparing with that of pressure. It is considered that this is due to the influence of high heat release rate when combustion oscillation occurs.



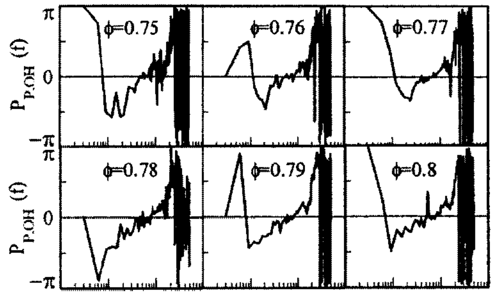
(a) Pressure



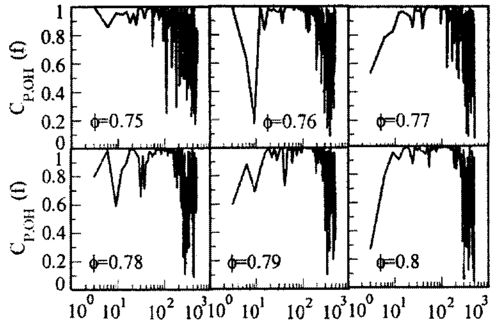
(b) OH-band emission

Fig. 7 Time series signals with the change of equivalence ratio

By observing these time-series data, we can easily judge the difference between phenomenon without combustion oscillation at equivalence ratio of 0.75 and phenomenon with combustion oscillation at equivalence ratio of 0.8. However, as for which equivalence ratio should be considered as the onset of combustion oscillation, it is difficult to judge quantitatively by observing only time-series data. If symptoms on the onset of combustion oscillation, that is a characteristic feature observed when combustion oscillation just begins to occur, can be detected by using any techniques, it is possible to prevent damages due to strong combustion oscillation in advance.

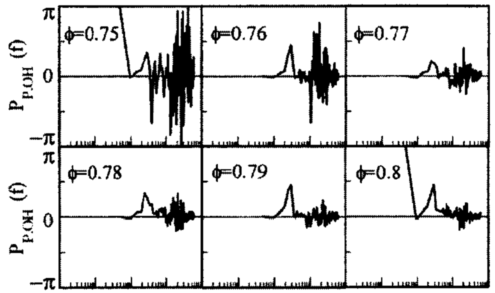


(a) Phase

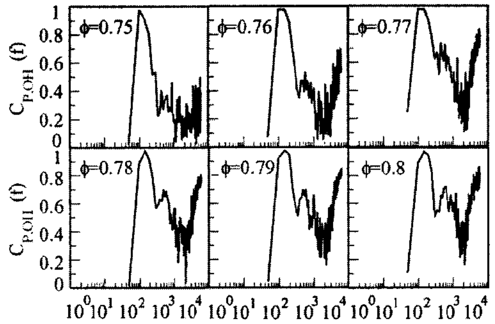


(b) Coherence

Fig. 8 Phase and coherence between pressure and OH in FFT with fine base frequency



(a) Phase



(b) Coherence

Fig. 9 Phase and coherence between pressure and OH in FFT with coarse base frequency

Therefore, in order to find out such a characteristic feature in obtained time-series data, a spectral analysis based on Fast Fourier Transformation (FFT) was conducted.

Figs. 8 and 9 show the phase and coherence between pressure and OH chemiluminescence as shown in Fig. 7, respectively. In Figs. 8 and 9, although the total number of data used for spectral analysis is 32,768, the setting for FFT process is different. For Fig. 8, the number of data for FFT is set at 2^{14} (=16,384, base frequency=3Hz), and the number of blocks for smoothing the obtained spectrum is set at 2. For Fig. 9, on the other hand, the number of data for FFT is set at 2^{10} (=1,024, base frequency=49Hz), and the number of blocks for smoothing the obtained spectrum is set at 32. Calculating method of the phase and coherence are as follows.

Time-series data digitized by an A/D conversion are converted into a complex spectrum by changing the number of data for FFT (2^n) and the number of block for smoothing the spectrum. If complex spectrum of time-series signal $f_i(t)$ is written as $F_i(f)$, power spectrum $W_i(f)$ of $f_i(t)$ and cross spectrum $X_{ij}(f)$ of $f_i(t)$ are expressed by following equations,

$$W_i(f)=F_i(f)\cdot\overline{F_i(f)} \tag{1}$$

$$X_{ij}(f)=F_i(f)\cdot\overline{F_j(f)} \tag{2}$$

where $\overline{F_j(f)}$ is the conjugate complex spectrum of $F_i(f)$. The subscript i and j are replaced by signals of pressure fluctuation (P) and OH chemiluminescence (OH), respectively. Phase $P_{ij}(f)$ is obtained as a deviation angle of complex cross spectrum by following equation.

$$P_{ij}(f)=\tan^{-1}\left[\frac{\mathrm{Im}(X_{ij}(f))}{\mathrm{Re}(X_{ij}(f))}\right] \tag{3}$$

That is, the phase means a phase difference between each frequency component of signal i and j. Coherence $C_{ij}(f)$ corresponds to cross-correlation coefficient in each frequency component of signal i and j and is calculated in following procedure. The absolute value of cross spectrum in each frequency component is normalized by geometric mean value of power spectrum of signal i and j.

$$C_{ij}(f) = \frac{|X_{ij}(f)|}{\sqrt{W_i(f) \cdot W_j(f)}} \tag{4}$$

In Fig. 8, both phase and coherence are largely fluctuated in high frequency range and correlation is not observed between two signals in all cases at equivalence ratio of 0.75 (no combustion oscillation) ~0.8 (onset of combustion oscillation). However, in Fig. 9(a), although the phase is largely fluctuated in high frequency range in case of equivalence ratio of 0.75, where no combustion oscillation occurs, the phase in high frequency range is slightly fluctuated around 0 radian in case of equivalence ratio of 0.8, where strong combustion oscillation occurs. In addition, the coherence in Fig. 9(b) also shows relatively high value in high frequency range. The difference between the results of Fig. 8 and Fig. 9 is due to the number of data for FFT (base frequency) and the number of blocks for smoothing the spectrum. In order to correctly analyze the data containing high frequency components, the result of Fig. 8, in which the number of data for FFT is large (2^{14}= 16,384) and the base frequency is small (3Hz), are considered to be correct, that is, indicating the actual phenomena.

If we observe the phenomena on average by processing the data with large base frequency (low frequency resolution) of FFT and with large number of blocks for smoothing the spectrum, the data analysis has enough frequency resolution for combustion oscillation in case of around 100Hz. However, it doesn't have enough frequency resolution for high frequency components near 1 kHz. This seemingly leads to results that high correlation (that is, coherence is high and phase is near 0 radian) is seen between pressure and chemiluminescence intensity in high frequency range, due to the influence of a higher order harmonic wave of low frequency range. If there is a peak frequency in pressure and OH chemiluminescence signals when combustion oscillation occurs, the fluctuations of high frequency range are nominally regarded as noise overlapped on large fluctuations of low frequency range. Therefore, in this case, if the data are processed by FFT with low frequency resolution (large base frequency), high correlation (that is, coherence is high and phase is near 0 radian) is seemingly seen between two signals in high frequency range, due to the influence of higher order harmonic wave of low frequency range. On the other hand, if the data without any peak frequency obtained in case of no combustion oscillation are processed by FFT, no correlation is seen between the two signals in all frequency range, where coherence and phase are largely fluctuated meaninglessly. In other words, relative power of high frequency component of signals is changed depending on the existence of peak frequency in low frequency range.

If this data processing method is used, the onset of combustion oscillation can be detected by observing the values of statistics (coherence and phase) in high frequency range. Therefore, this is expected to be useful technique for detecting the symptoms of combustion oscillation.

4. Conclusions

We conducted the experiments focusing on usefulness of chemiluminescence measurement by using an optical fiber and detection on symptoms of self-excited combustion oscillation. The obtained concluding remarks are summarized as follows.

1. In case where the self-excited combustion oscillation occurs, because there is high correlation between chemiluminescence intensity obtained as the summation of all pixel intensity of chemiluminescence images taken by a high speed CCD camera and chemiluminescence intensity collected by an optical fiber, OH chemiluminescence measurement by an optical fiber is effective technique in detecting combustion oscillation.
2. In order to detect the symptoms of combustion oscillation, we investigated carefully the transient process leading to combustion oscillation by gradually increasing the equivalence

ratio at interval of 0.01. As a result, it was found that, in case where combustion oscillation begins to occur, the cross-correlation coefficients between pressure and chemiluminescence intensity are abruptly dropped because two different phenomena, in which pressure and chemiluminescence intensity are fluctuated with high correlation or low correlation alternately. However, once the strong combustion oscillation is occurred, the cross-correlation coefficients are increased. Therefore, the drop of cross-correlation coefficients can be used as the symptoms on the onset of combustion oscillation.

3. If we observe phenomena on average by processing the data with large base frequency (low frequency resolution) of FFT and with the large number of blocks for smoothing the spectrum, the phase is fluctuated near 0 radian in high frequency range. By using this, it is possible to detect the symptoms of combustion oscillation.

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The authors thank Professor Ken Kishimoto of Kokushikan University for many useful discussions on the spectral analysis.