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Conical Flameholder with Pilot Burner for Lean Premixed Combustion

Takeshi YAMAMOTO, Yoji KUROSAWA, Shigeru TACHIBANA,
Seiji YOSHIDA, Kazuo SHIMODAIRA and Kazuo SUZUKI

Aeronautical Environment Technology Center, Institute of Space Technology and Aeronautics,
Japan Aerospace Exploration Agency
7-44-1 Jindaiji-higashi-machi, Chofu, Tokyo 182-8522, JAPAN
Phone: +81-422-40-3469, FAX: +81-422-40-3440, E-mail: yamamoto.takeshi@jaxa.jp

ABSTRACT

A new type flameholder was designed aiming low NOx emission from gas turbines. It has conical shape with slits. The flameholder and a conventional swirl type one are tested experimentally. Each of them has a pilot flame. Methane is used as fuel. The result shows that the conical flameholder enables high combustion efficiency in leaner conditions as compared to the swirl type one. It is also shown that the conical flameholder cause oscillatory combustion at lower power level and at higher equivalence ratio condition region than the swirl type one.

NOMENCLATURE

C_{NOx}: Concentration of NOx corrected to 15 % O_2 condition, ppm
ERc: Overall equivalence ratio
LCE: Local combustion efficiency, %
LER: Local equivalence ratio
PP: Percentage of fuel flow rate for the pilot mixture, %
Ta: Temperature of the supplied air, K
Uc: Mean velocity at combustion chamber, total mixture divided by the cross-section of the combustion chamber, m/s
x, y, z: Cartesian coordinates

INTRODUCTION

Lean premixed combustion is one of the most attractive methods to reduce NOx emission from gas turbines. However it has a drawback that suitable equivalence ratio range which can offer stable and high efficiency combustion is very narrow as compared to diffusion combustion. At ultra-lean conditions, which are preferable for reducing NOx emission, it is difficult to obtain enough combustion efficiency. On the other hand, in high thermal load conditions, intense oscillatory combustion occurs commonly. The objective of this study is developing a flameholder that offers high combustion efficiency at ultra-lean conditions and stable combustion in wide equivalence ratio range.

Various types of flameholders have been studied (Roffe et al., 1978, Lovett et al., 1992 and Roquemore et al., 2001). Lovett et al. (1992) tested bluff-body, perforated-plate and swirl type flameholders in lean conditions. The study showed that the type of flameholder has little effect on the NOx emissions, and swirl type flameholder is most excellent in terms of flame stability. Swirl type flameholder is widely used for gas turbine combustor. It is often used with a pilot burner for stabilization of the flame. But bluff-body type flameholders accompanied by the pilot burner is not studied sufficiently.

A new type flameholder, which is named conical flameholder, is designed and tested (Yamamoto et al., 2002a, 2002b, 2003a, 2003b). The study showed that the conical flameholder offers high combustion efficiency at ultra-lean conditions in short combustion chamber. Combustion characteristics of the conical flameholder and the swirler type one on premixed combustion of air and methane are compared in this paper.

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APPARATUS AND PROCEDURES

Flameholder models

Two types of flameholder model are tested. One is the conical flameholder. The other is a swirl type one. Swirl type flameholder is generally used and is accomplished by diffusion type pilot burner. But it is known that diffusion flame generates much NOx. Therefore premixed type is selected as the pilot flame in this study. Pilot mixture needs higher equivalence ratio than main mixture for stability of the pilot flame. It results higher NOx concentration than that by main flame. It is necessary to reduce the pilot mixture for ultra-low NOx emission.

For small gas turbine and gas turbine for airplane, the combustor length must be short. To obtain high combustion efficiency in a short distance at ultra-lean condition, the contact area of main mixture and burned gas generated by pilot burner must be large. To do that, it is needed to disperse the pilot flame in whole combustion chamber. A bluff-body seems to be efficient to lead the burned gas to radial direction. Based on these facts, the conical flameholder was designed. Figure 1 shows concept of the flameholder. Pilot mixture flows into inside of the flameholder through small holes and forms a stable pilot flame. Burned gas made in the pilot flame runs to radius directions along inner surface of the flameholder. Main mixture flows into through slits made on side of the cone and is ignited by the burned gas. Figure 2 is a photograph of the flameholder taken from downstream. The diameter of the cone is 100 mm and depth is about 90 mm.

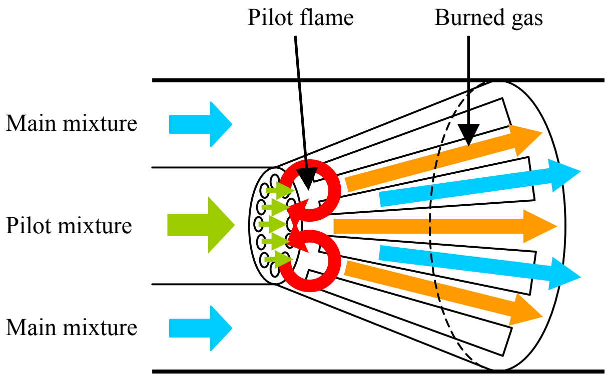

Fig. 1 Concept of conical flameholder

Figure 3 shows swirl type flameholder. It has two swirlers, which make clockwise flow. The pilot mixture is supplied through the inner swirler and the main mixture flows into through the outer swirler. The blade angle of both swirler is 30 degrees on mid-span. Over all swirl number is about 0.45. The dimensions of cavity at the center are same with that of conical flameholder. The opening area of the main swirler is same with that of slits on the conical flameholder projected to a plane that lies at right angle with combustor center axis.

Test Rig

The combustion test rig is illustrated schematically in Figure 4. The flameholder is placed in a duct, which inside diameter is 100 mm. The left end of flameholder is connected to the pilot premix tube. The right end of the duct is connected with the combustion chamber. It has four windows made of quartz glass. The inside measurements are 214 mm in length and 100mm in width and height. The right end of the combustion chamber is open to the atmospheric pressure. Electrically heated air flows into the duct from the left side and is mixed with fuel at pilot mixer and main mixer. Methane is used as fuel. To make a uniform mixture, the main mixer is composed of many air passages, which have fuel injections. Pilot mixture and main mixture flow through their own premix tube and are supplied to the flameholder. The origin of the coordinates is placed at the center of combustion chamber exit. The center axis of the combustor is x, horizontal axis is y and vertical axis is z.

Instrumentation

For evaluating the flameholders, it is necessary to know the composition of gas at local points in the combustion chamber. Gas sample is withdrawn from the combustion chamber by a sampling probe. The probe has diameter of 8 mm, 1.6 mm sampling hole at its tip and passage for hot-water-cooling. The sample line from the probe to the gas analyzer is heated by an electrical heater to prevent condensation of water. Gas is analyzed by MEXA-9110H (HORIBA, Ltd.). The concentrations of 5 chemical species (CO, CO_2, Total HC, O_2 NOx) are measured.

Unsteady pressure in the combustion chamber is also measured. Pressure transducer is XTME-190 (Kulite Semiconductor Products, Inc.). It is placed at x=-178, z=0 accompanied by water-cooled adapter.

Fig. 2 Conical flameholder

Fig. 3 Swirl type flameholder

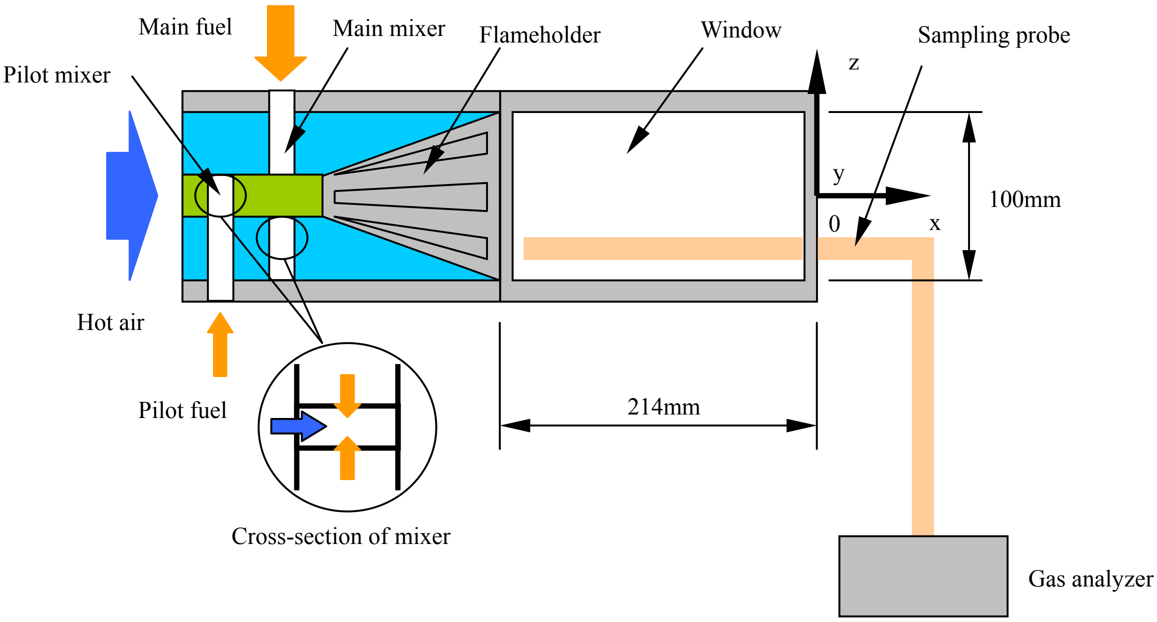

Fig. 4 Schematic of test rig

Test Procedure

This study places emphasis on the progress of combustion and NOx emission at ultra-lean conditions and the combustion oscillation at high equivalence ratio conditions. The conditions of former case are shown in Table 1. The condition L1 is lean condition and it is used for comparisons with ultra-lean conditions. The condition L2 is different from L1 in ERc. The conditions from L3 to L6 are different from L1 in Ta and are different from each other in PP. The L7 is different from L1 in Uc. In these conditions, gas analysis in the combustion chamber is conducted. The conditions of latter case are shown in Table 2. H3, H4 and H5 are different from each other in PP. In these conditions, pressure fluctuation in the combustion chamber is measured and analyzed.

Table. 1 Experimental conditions of ultra-lean case

No.	Uc, m/s	Ta, K	ERc	PP, %	Flameholder
L1	15	700	0.50	3.0	Both
L2	15	700	0.44	3.0	Both
L3	15	600	0.50	2.3	Both
L4	15	600	0.50	2.5	Both
L5	15	600	0.50	3.0	Both
L6	15	600	0.50	5.0	Swirl type
L7	30	700	0.50	3.0	Both

Table. 2 Experimental conditions of high ERc case

No.	Uc, m/s	Ta, K	ERc	PP, %	Flameholder
H1	15	700	0.58	2.0	Swirl type
H2	15	700	0.65	2.0	Conical
H3	15	700	0.70	1.2	Conical
H4	15	700	0.70	2.0	Conical
H5	15	700	0.70	3.0	Conical

RESULTS AND DISCUSSION

Ultra-lean conditions

Fig. 5 is the distributions of the local combustion efficiency LCE on the y-axis in the conditions L1 and L2. The figure shows that the conical flameholder has high LCE at the every measurement point on the y-axis in both conditions. Flame was observed on the inner surface of circumference part of the conical flameholder in both conditions. Fig. 6 shows distribution of oxygen molecular concentration on the plane x=-200, 14mm downstream from the backward-facing step in the condition L1. The concentration is not the value that is calculated taking the water molecule into account. LCE could not be measured, because the concentration of THC in some region exceeded the range of the gas analyzer. The concentration is low around the center (y=z=0) and near the walls. It means that burned gas exists in these regions. The burned gas generated on the internal circumference flows into the back-step region. The conical flameholder forms pilot flame around the center axis and on the inner surface of circumference part. Fig. 6 also shows that the ribs of the flameholder have some effect to promote the combustion (center lines of the rib are shown by solid lines). Therefore the conical flameholder can offer high LCE at all points in both conditions.

Swirl type flameholder has high LCE at every point in the condition L1. The flame in the back-step region was observed in the condition L1. Therefore every point has high LCE in this condition. But in the condition L2, the LCE is low at the points near the wall. The flame in the back-step region is not observed in this condition. Figure 7 shows the LCE distribution in the combustion chamber with swirl type flameholder in condition L2. The contour of the upper region (y>0) is copy of the data measured in the lower region (y=<0). High LCE region is formed in the recirculation zone and its downstream region. The LCE is almost 0 in the back-step region. Main mixture flows outside of the recirculation zone. The velocity seems to be much faster than Uc, because the blockage of the recirculation zone is big. The inner part of the main mixture flow is mixed with the burned gas in the recirculation zone by turbulence and burns there. The middle part flows into behind the recirculation zone and mixed with burned gas flow from the recirculation zone and burns. The outer part flows at high velocity along the wall surface to the exit and the burned gas is supplied from the inner burned region, which flows parallel to the wall. Therefore combustion progresses slowly as compared to the velocity and it resulted the low LCE near the wall.

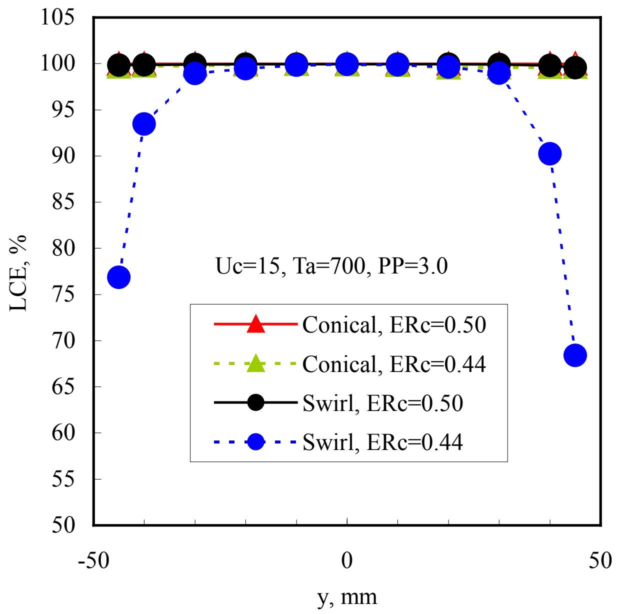

Fig. 5 LCE distributions (influence of ERc)

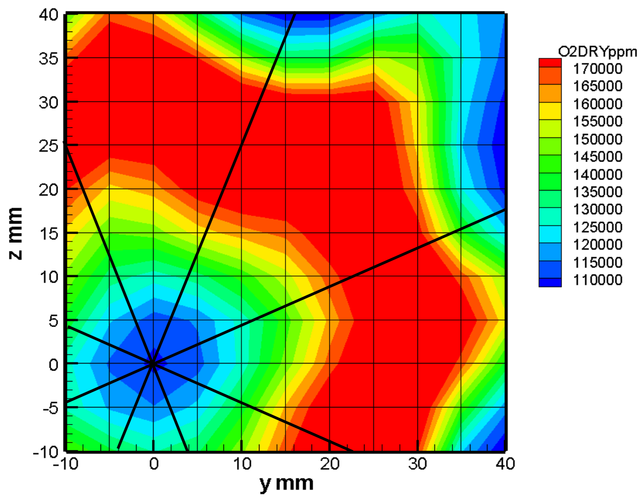

Fig. 6 O_2 concentration distribution at x=-200 (Uc=15, Ta=700, ERc=0.50, PP=3.0)

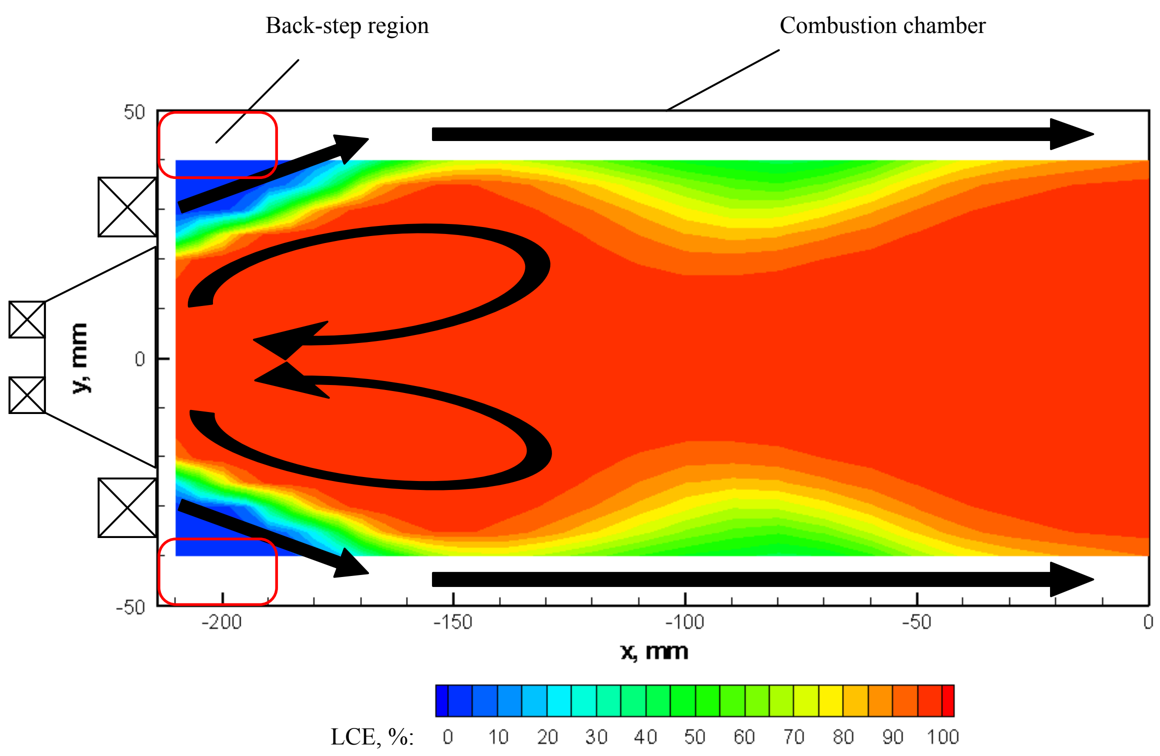

Fig. 7 LCE distribution (15m/s, Ta=700K, ERc=0.44, PP=3.0)

Fig. 8 shows the distributions of the NOx concentration on the y-axis in the conditions L1 and L2, which are different from each other in ERc. The concentration is the value that is calculated taking the water molecule into account and is corrected to the 15 % O_2 condition. It shows that the influence of the flameholder configuration is small and the influence of the total equivalence ratio ERc is big. This result agrees with the conclusions by Roffe et al. (1978) and Lovett et al. (1992).

Fig. 9 shows the distributions of the LCE on the y-axis in the conditions L1 and L5, which are different from each other in Ta. Fig. 10 is the distributions of the LCE in the conditions L1 and L7, which are different from each other in Uc. The conical flameholder offers high LCE at the every point in all conditions. The swirl type flameholder has low LCE points near the wall in the conditions L5 and L7. It can be concluded that the conical flameholder completes the combustion in shorter combustion chamber than the swirl type one.

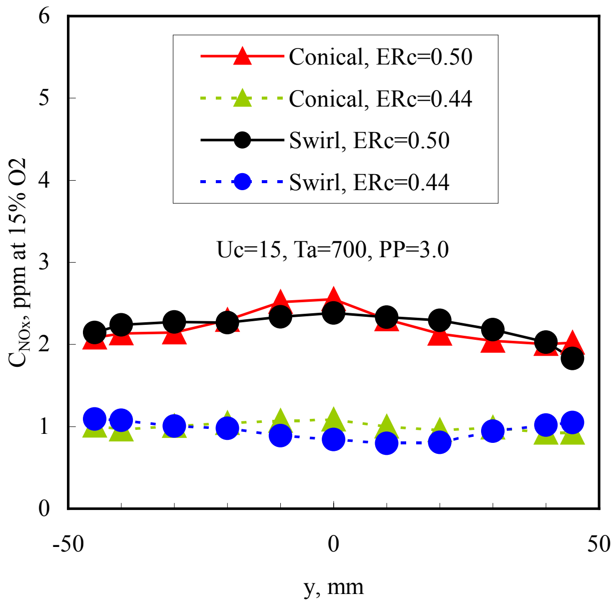

Fig. 8 NOx concentration distribution (influence of ERc)

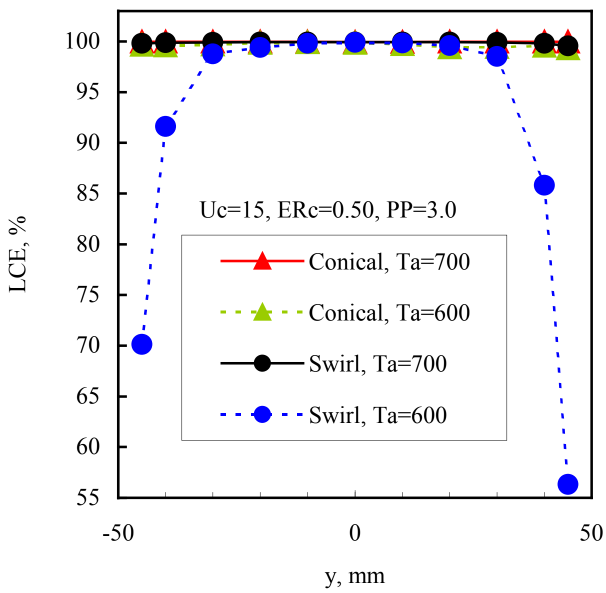

Fig. 9 LCE distributions (influence of Ta)

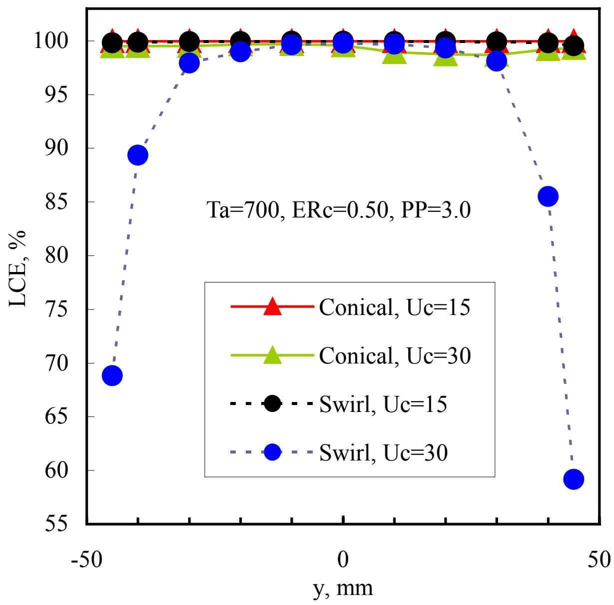

Fig. 10 LCE distributions (influence of Uc)

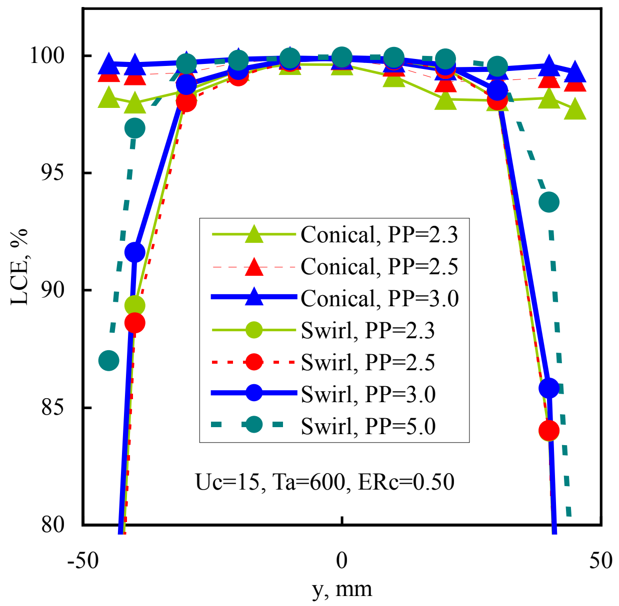

Fig. 11 LCE distributions (influence of PP)

Combustion control by pilot fuel

Fig. 11 shows the distributions of the LCE on the y-axis in the conditions from L3 to L6, which are different from each other in PP. As the percentage of the pilot fuel PP increases, the LCE of the conical flameholder rises, and the LCE of all measurement points exceeds 99.5% when PP is 3.0. The LCE of the swirl type rises gradually as PP increases, but it is not enough even in the condition L6, which has PP of 5.0 %.

Fig. 12 shows the distributions of NOx concentration on the y-axis in same conditions with Fig. 11.This figure shows that the NOx concentration distributions of the conical flameholder shifts about 0.5 ppm by increase of the PP. In regard to the swirl type flameholder, the NOx concentration distribution is almost same in the conditions L3, L4 and L5. But in the condition L6, it is very high.

The center of the flameholder cavity exit was selected as typical point of the pilot flame. Fig. 13 is the relationship between PP and LER/ERc at this point. The figure shows that LER/ERc of the conical flameholder is proportional to PP. As PP increases, the temperature of pilot flame rises. It resulted the increase of NOx concentration shown in figure 12. The conical flameholder can control the NOx concentration to minimum by using minimum pilot fuel flow rate to obtain enough combustion efficiency.

On the other hand, LER/ERc of the swirl type flameholder gradually changes in the condition of PP=2.0-3.0. It is because the main mixture dilutes the gas in the recirculation zone. When PP=5.0%, LER/ERc is comparatively high. Choking of the pilot air by the fuel injection seems to occur it. It resulted the high NOx concentration shown in figure 12. Even the pilot flame with high equivalence ratio can’t sufficiently raise the local combustion efficiency in near the wall as shown in figure 11. To obtain high combustion efficiency by the swirl type flameholder in short combustion chamber like gas turbine engines for airplane, it is necessary to raise the equivalence ratio of the main mixture.

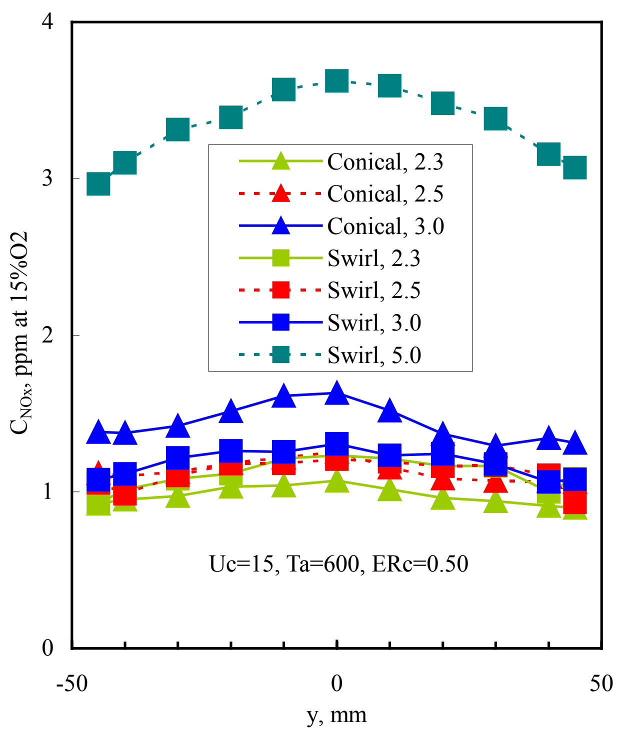

Fig. 12 NOx concentration distributions (influence of PP)

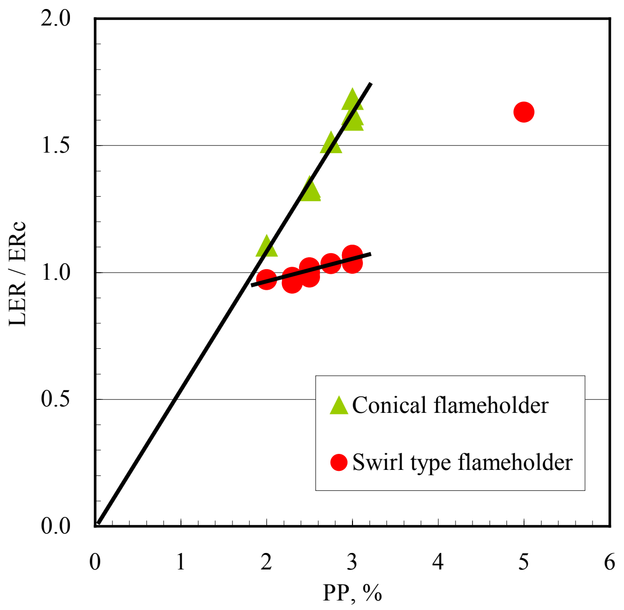

Fig. 13 Relationship between PP and LER/ERc

Combustion Oscillation

Keeping the average velocity Uc to 15 m/s and the air temperature Ta to 700 K, the combustion oscillation was investigated by measuring the pressure in the combustion chamber. When the total equivalence ratio ERc was increased gradually, the flame stabilized by the swirl type flameholder started to cause combustion oscillation at the ERc of 0.58 (condition H1). Fig. 14 shows the power spectrums of the pressure in the conditions H1, H2 and H4. The spectrum in the condition H1 has one high peak at 463 Hz. The frequency corresponds to that of the oscillatory wave whose wavelength is four times the length of the premix tube. Therefore the combustion oscillation seems to be occurred by equivalence ratio fluctuations of main mixture.

In regard to the conical flameholder, the oscillation rose at the ERc of 0.65 (condition H2). The power spectrum has two peaks (480 and 786 Hz). The peak at lower frequency (480 Hz) is resonance in premix tube and the peak at higher frequency (786 Hz) corresponds to that of the oscillatory wave whose wavelength is four times the distance from the pilot burner to the combustion chamber exit. The heights of two peaks are much lower than that of the swirl type observed at the ERc of 0.58. The ERc in which the peak of the conical flameholder rises to same power level with the swirl type is 0.70 (condition H4). The spectrum also has two peaks (490 and 805 Hz) and the type of oscillation is same with that of the condition H2.

From the results mentioned above, the conical flameholder starts to cause the combustion oscillation at higher ERc and has lower oscillation strength than the swirl type flameholder. The flame stabilized by the swirl type flameholder is short and the heat release is concentrated. The concentration of heat release often causes strong combustion oscillation. On the other hand, the conical flameholder has the flame that spreads from the pilot cavity to the back-step region. It seems that the dispersion of the heat release suppress the combustion oscillation.

Fig. 15 shows the power spectrums of the pressure in combustion chamber in the conditions H3, H4 and H5, which are different from each other in PP. The spectrums of conditions H4 and H5 have two low peaks. When the PP is decreased (condition H3), the high frequency peak diminished and new peak 990 Hz occurred and lower peak 465 Hz became very high. The frequency 990 Hz corresponds to that of the oscillatory wave whose wavelength is four times the length of combustion chamber. The decrease of the pilot fuel declines the flame temperature and the heat release in the pilot flame. The heat release is concentrated in the back-step region and the resonance in the combustion chamber rises. The peak at lower frequency is also raised to very high level. This change of the combustion oscillation mode and power level by PP shows that the dispersion of the heat release suppresses the combustion oscillation. More investigations are necessary for clarifying the suppression mechanism of the combustion oscillation by the conical flameholder.

CONCLUSIONS

Combustion characteristics of the conical flameholder and the swirl type flameholder were compared on premixed flame of methane and air.

In the ultra-lean conditions, the local combustion efficiency at exit of the combustion chamber and inside of the chamber is measured by conducting gas analysis. The conical flameholder showed high combustion efficiency at all exit measurement points in ultra-lean conditions as well as lean conditions. The flame stabilized by the swirl type flameholder has slow progress in the outer region of the swirl flow in the ultra-lean conditions.

The distributions of the local combustion efficiency and NOx concentration of the conical flameholder rose as the pilot fuel increased. It shows that the conical flameholder can control the NOx concentration to minimum by using minimum pilot fuel flow rate to obtain enough combustion efficiency. As for the swirl type, the effect of the pilot fuel flow rate on the combustion progress is small because of dilution of the recirculation zone by the main mixture. To obtain high combustion efficiency in short combustion chamber by the swirl type flameholder used in this research, it is necessary to use main mixture of enough equivalence ratio.

In the high equivalence ratio conditions, the power spectrums of pressure in the combustion chamber were measured and compared. The conical flameholder starts to cause the combustion oscillation at higher overall equivalence ratio and has lower oscillation strength than the swirl type flameholder. And it is also found that the conical flameholder with enough pilot fuel suppresses the combustion oscillation.

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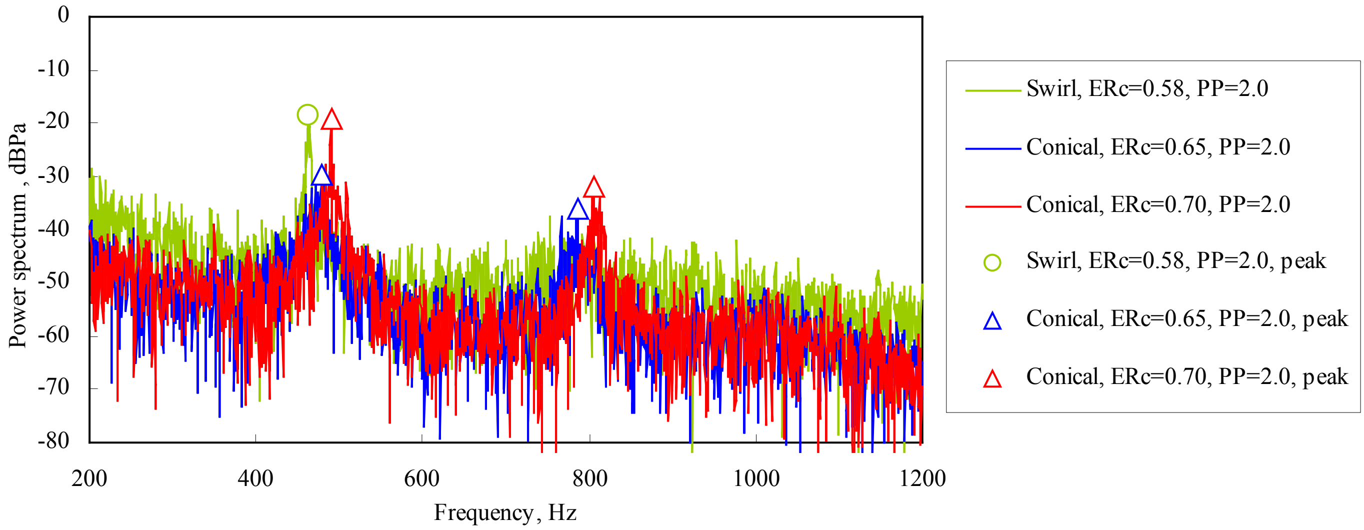

Fig. 14 Power spectrums of pressure in combustion chamber

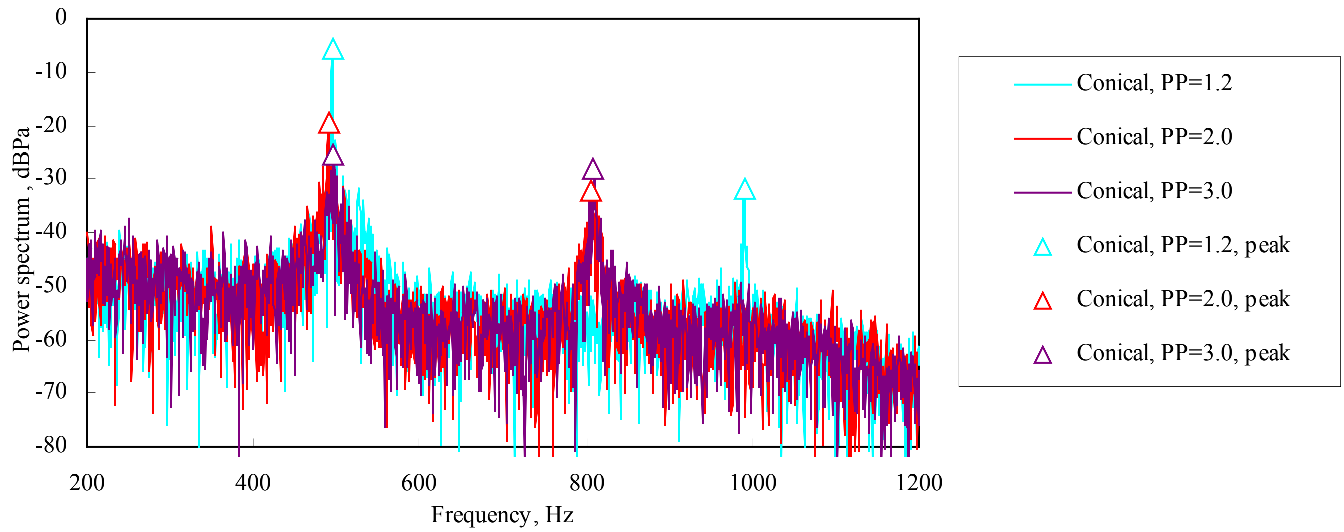

Fig. 15 Influence of PP on power spectrums of pressure