Efficiency of Air Injection on Stability and Emission Controls in Premixed Combustion

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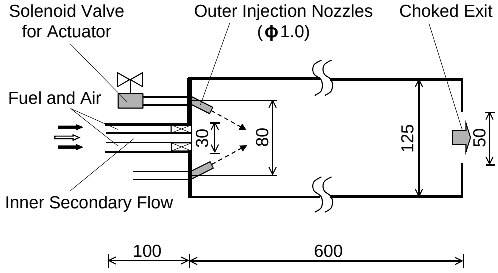
Introduction

It is well known that the self-excited large unsteady flow oscillations in combustors have some problems for developing the gas-turbine engines. Lean premixed combustion is used to reduce NOx emissions, however, thermoacoustic instability is formed close to the flammability limit. Therefore, feedback control to interrupt the coupling effect between thermoacoustic and heat release oscillations has been suggested for a wide range of equivalence ratio with a robust operating [e.g., 1-3]. For example, several secondary injection methods as an active combustion control (ACC) have been reported to develop an effective way suppressing the pressure oscillation. As the working fluid for secondary injection, we can use fuel- or air-based additions for each purpose. The secondary fuel injection would mean to modify the inhomogeneous distribution of equivalence ratio in combustion zone. In this regard, periodic secondary fuel injection has a performance suppressing the pressure oscillation [4, 5]. However, there is a possibility to increase NOx emissions due to the injection of overloaded fuel. In that case, it is important to optimize the amount of secondary fuel injection and injection method. On the other hand, the air secondary injection would mean to modify the same problem on the hot spots cased by the inhomogeneous distribution of equivalence ratio. Furthermore, we can expect that the structure of flame will be modified due to the momentum effect of the injection [6, 7]. In this regard, the secondary air injection seems to be benefit to suppress the pressure oscillation and to reduce the NOx emissions. Air -jet momentum effect as a secondary addition has a possibility to reduce the instability caused by both effects of heat loses and strain rate which is characterized by heat release rate distribution and vortex behavior, respectively.

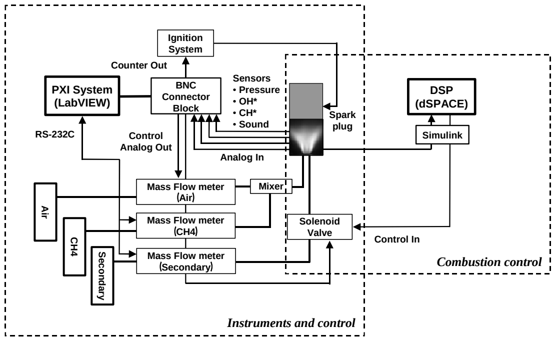
The present experiments were performed in a swirl-stabilized combustor in which a dominant oscillation mode would correspond with the Helmholtz-type resonance. In this paper, we show the performance of air-jet injection caused by outer injection nozzles around the swirl-stabilized flame to reduce the combustion instability without modification of the major geometric design of the flame holder. Particularly, we show the results of ACC system established by the air-jet injection using $H\infty/H2$ hybrid mixture-controller.

Experimental Apparatus

A schematic of the experimental combustor including the control system is shown in Fig. 1-a. The combustor consists of a rectangular stainless steel duct with 600-*mm* length in flow direction and 125-*mm* squire in cross-sectional aria as a test section. The test section is equipped with quartz windows for optical applications. The swirl-type anchoring nozzle is used for the mixing between methane and air. In this study, periodic air-jet as a secondary working fluid is injected into the oscillatory flame with the angle of 60 degrees to vertical axis. The secondary injection nozzle has a 1.0-*mm* small hole in diameter, and six nozzles are equipped around the flame holder. Measurement and control system is described as shown in Fig. 1-b. As for the measurement and its control, an auto instruments/control system is developed using the PXI system installed the LabVIEW® (National Instruments Co.). The system equips the BNC connector block for input and output analog-signals, and it can be used as a data logger or a function generator. Pressure fluctuation, OH* and CH* chemiluminescence are sensed with pressure transducer (4043A; Kistler) and photo-diode (S2281-04; Hamamatsu Photonics). Furthermore, phase-locked OH* chemiluminescence images are taken by the high-speed camera (NanoStar; LaVison) with image intensified unit and band-pass filter (310 ± 10 nm). The PXI system controls mass flow meter units with analog output signals, and ignition is also done automatically with the system. The periodic secondary air-jet is generated by the servo-valve (58A-262;HSC Controls Inc.) installed sin-curve signal. As for the feedback control system, the digital signal processing board (DS1103; dSPACE) is used for installing and operating the developed controller.



(a) Configuration of test combustor.



(b) Measurement and control system.

Figure 1. Schematics of experimental apparatus.

Results and Discussion

In the case of oscillatory flame condition, phase-locked OH* chemiluminescence images are taken to clarify the flame structure based on exothermic. Figure 2 indicates the result of OH* images. The mass flow rates of methane and air are 12 and 152 *l*/min, respectively. In that case, the equivalence ratio is 0.75. The pressure fluctuation is applied to a trigger signal for high-speed camera. Because of the

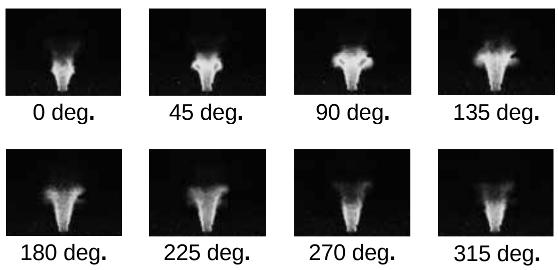


Figure 2. OH* chemiluminescence images of an oscillatory flame.

recirculation flow pattern near the flame holder, hot spots are formed at the downstream as shown in the image of 45 or 90 degrees which means the situation of a strong pressure oscillation. It is supposed that the hot spots correspond to the equivalence ratio fluctuation. So it is important to control the distribution of the equivalence ratio.

When we consider controlling the oscillatory flame, it seems that the secondary injection can be useful to a better operating condition. Furthermore, the secondary injection has a possibility to change flame structure with several efficiencies of the exothermic control, improvement of flow pattern including vortex, and so on. In this study outer secondary injection method is carried out to reduce the pressure oscillation. The outer injection means secondary-jet form the circular arranged nozzle around the flame holder. Figure 3 shows efficiency of the secondary jet with not periodical injection but steady one. As for the secondary working fluids, methane, hydrogen and air are used to improve flame structure. In the same figure OH* fluctuation is also indicated. Each working jet shows a performance to suppress the pressure oscillation. However, secondary fuel injections indicate an increased trend of pressure and OH* fluctuations with an increase in secondary flow rate under certain conditions. As for the most effective jet, the secondary air has a good performance to suppress the pressure oscillation and to reduce the heat release fluctuation with small amount of the injection rate. With just 1 % amount (Q_s=1.5 *l*/min) of the additional air-jet, the performance is achieved successfully.

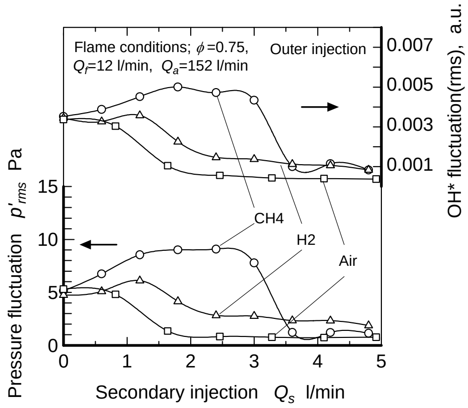


Figure 3. Effects of secondary jet on suppressing the pressure fluctuation.

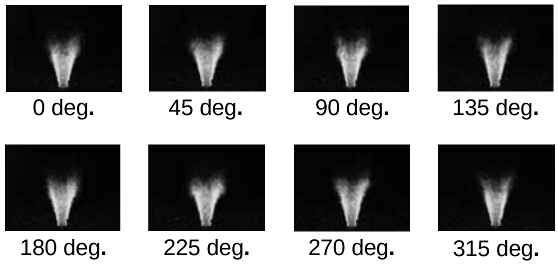


Figure 4. OH* chemiluminescence images of a steady flame (controlled with steady injection jet of Q_s=1.5 *l*/min).

Figure 4 shows phase-locked OH* chemiluminescence images in the condition of Q_s=1.5 *l*/min. This situation is an almost steady flame with a week pressure oscillation. Comparing the result with that of Fig. 2, flame structure is changed into homogenous distribution without hot spots. From the images the vortex generated in recirculation zone seems to disappear due to the momentum effect of the secondary air-jets. Thus controlling the flame structure using momentum effect is effective for the oscillatory combustion.

According to the results of secondary air-jet, next challenge is to apply a feedback control on the instability flame using the secondary air-jet. Figure 5 indicates the block diagram of developed control system. The concept of developing the control system is to reduce the dominant resonance frequency with H2 controller and to consider the robustness with H∞ controller. In the block diagram $G(s)$ is a transfer function of the system, $K(s)$ is a controller, Z_{21} is the performance index based on H∞ norm for the input signal, Z_{22} is the performance index based on H2 norm for the output signal, respectively. As for the determination of the transfer function $G(s)$, the system identification method is used considering the delay-time in the system. The controller $K(s)$ is designed by solving a mixed H∞/H2 control problem.

Performance of the developed controller is described in Fig. 6. Main flame condition is an oscillatory flame characterized with Q_f=12 *l*/min; fuel flow rate, Q_a=152 *l*/min; primary air, Φ=0.75; equivalence ratio. As the control condition, additional air-jet is supplied with Q_s=3 *l*/min from the outer nozzles. When the secondary is injected, overall equivalence ratio seems to be almost the same value. From the result, the developed controller works well to reduce the pressure fluctuation. Under the control, the secondary air-jet is injected with periodic frequency like sinusoidal. In addition, although the air-jet injected with steady flow has ability to reduce the pressure fluctuation as shown in Fig. 3, it is clear that the pulsation supply of the secondary has a good performance compared to the steady flow injection (see Fig. 3).

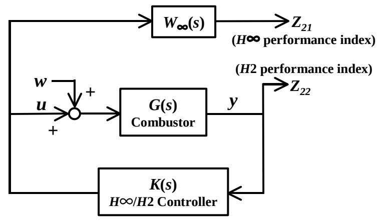


Figure 5. Block diagram of H∞/H2 hybrid controller.

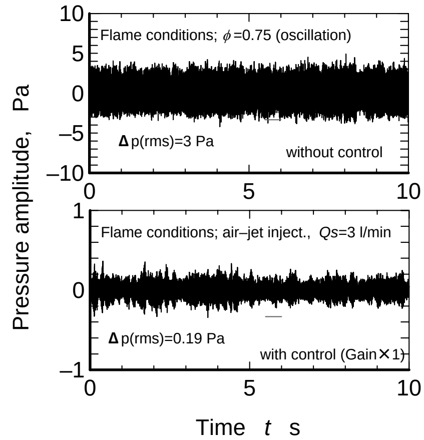


Figure 6. Performance of H∞/H2 hybrid controller.

Concluding Remarks

Control technique to the self-excited oscillation in premixed combustor is investigated using the secondary injection from outer nozzles to the main flow. Methane, Hydrogen and Air injections are carried out to reduce the pressure fluctuation and to improve the flame structure. A few amounts of the additional air-jet injected periodically shows good performance to suppress the pressure fluctuation, and furthermore it can be effective to improve the flame structure. As for the emissions control, NOx reduction is achieved with the air-jet. The result will be shown in the presentation.

Acknowledgement

This work was supported by the Ministry of Education, Culture, Sports, Science and Technology, Project for Organized Research Combination System.

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