Study on Active Control of Combustion Oscillations for Lean Premixed Combustion Systems

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Abstract

Methane premixed flame is studied extensively using a swirl burner and a swirl combustion chamber. First the fundamental study for the flame properties is performed for the swirl burner. Flame configuration is analyzed by a high speed photography and Schlieren system. Then a control system is set up using MATLAB, Simulink, PPC Controller board, dSPACE, and an actuator.

Two control systems are applied in the present study; one by using a mass flow control system and another by using a speaker. In the mass flow system the premixed flame is controlled by the certain threshold. In the speaker system the premixed flame is controlled on and off arbitrary using the sensor and actuator. A half frequency of the primary frequency of noise is detected to be eigen value, but is investigated where this frequency comes from. The present systems are open loop system and closed system will be established soon.

1. Introduction

Our important goal is to establish a combustion system of high efficiency and low emission of polluted gas and noise. To this goal the governmental project on "Smart Control of Turbulence" is started to develop new concepts, new methods, and new devices. Candel described that dynamic behavior of steady flames are known to cause noise, vibrations, and failure in heating and power systems; furnaces, boilers, and gas turbines [1]. Flame stabilization have been discussed in the past [2] that a pilot flame is most reliable one for gas turbine to start with. Instability and oscillatory combustion appear in gas turbine combustion chamber, boiler, etc. Such combustion causes the malfunction of combustion system, mechanical oscillation, unpleasant sound, and NOx and COx. To control the system there are the passive control, which can be performed through basically designing the combustion chamber shape, and the active ressure and to control the mass flow rate and the speaker sound. Many passive controls have been studied up to now, but less active controls have been worked.

Flame holder and bluff bodies are also used to stabilize flames for many purposes [3]-[5]. Flame oscillation control has been studied passively [6] and actively [1],[7],[8]. Especially Zinn has been active in this field for long time and published from passive to active control studies [9-13]. Ghoniem study the control system differently from Zinn. He analyzed active control system based on the flame dynamics [14]. Kuentzmann et al.[15] applied a neural network system to combustion control. Some studies of active combustion control are a neural network system by Kuentzmann et al.[15], LOG-LTR control by Ghoniem et al.[16], open and closed loop control system by McManus et al.[17]. Zinn et al.

[18] presented the active control of lean premixed flame oscillation. Positive points of active control for flame are to prevent flame quenching, blown out, oscillating, and noise.

The present study is to construct a basic combustion control system and to control a lean premixed methane/air flame combustor.

2. Experimental System

Experiments are performed using a methane/air lean premixed combustor, which combustion chamber is attached or detached whether the flame or chamber combustion is studied. A swirler is installed to stabilize flame, where three different swirl angles are 15, 30, and 45 degrees and the swirl numbers are 0.162,0.334, and 0.519, respectively.

Figure 1 shows the total experimental system with a control system. Methane and air are provided by high pressure cylinders through reverse flow control valves and mass flow controllers to mix them together in the mixer and to flow into the premixed combustion chamber. Especially air is separated into two; one for mixing with methane after its flow rate is controlled by the control panel and the other for controlling air by a PC through dSPACE. The premixed burner and combustion chamber are briefly described in Fig.2, where after the mixture is input in this system, the mixture goes through a settling chamber with a couple of meshes.

A swirler is installed in the nozzle part of the burner to provide a swirling to the mixture at the combustion chamber, which is shown in Fig. 2



3. Experiments

Unstable combustion occurs at the exit of swirl burner in the specific mixture. This may come from the fluctuation of combustible hot spots or the interaction between inner and outer flames. The unstable factor is related with the turbulent structure being built by mixture and outer flows. It is one way to activate or non-activate such turbulent flows to control combustion. In the present study a speaker is used to provide an oscillation to the flow field. Especially a focusing speaker originally made is installed in order to concentrate the sound energy at the area in the combustion chamber. A microphone is used in the first place as a sensor for controlling the system. However this time the open loop control system is applied for the

oscillating combustion system since we did not get a control function yet.

Two ways are applied for suppressing the flame oscillation: a control by a mass flow meter and a control by a speaker. The former is formed by setting a known threshold to quench such oscillating combustion and the latte is done by a open loop system using the speaker actuator.

	Mass flow control	Speaker control	
Fuel (l/min)	CH4 0 \sim 7	CH4 0 \sim 7	
Oxidizer (l/min)	Air $0 \sim 85$	Air $0 \sim 85$	
Re number	$0 \sim 4050$	$0 \sim 4050$	
Swirl number	0.162(15°), 0.334	$4(30^{\circ})$ 0.519(45°)	
Jet velocity (m/s)	$0~\sim 2.2$	$0 \sim 2.2$	

Table1. Experimental Conditions

4. Control Systems

In this study two different open control systems are applied to the burner and combustion chamber system. As described in the experimental system, the mass flow control experiment is performed by the system shown in Fig.3, where the sound level meter senses the combustion chamber noise. The dSPACE board controls the flow rate of the mass flow through the PPC control board and the output of flow rate signal goes to the dSPACE through the PPC control board. Figure 4 shows the relation among MATLAB, Simulink, PPC. Controller board, dSPACE, and the actuator.



Fig.3. Block-diagram describing model controller architecture



Fig.4 Real-Time Controller Board

5. Experimental Results

5.1 Fundamental features of burner flame and chamber flame

5.1.1 Methane premixed swirl burner flame without combustion chamber

Characteristics of methane premixed swirling flame have been studied in order to know their fundamental properties. Figure 5 shows the flammability limits to methane flow rates. Flashback is observed at the condition of methane flow rate of 2.5 [l/min] without swirling and that of 1 [l/min] with a swirl angle of 15 degrees. The limit of flashback is about stoichiometric condition and flashback is not seen less than that.

Figure 6 shows the NOx concentration to the equivalence ratio of methane/air flame. The prompt NOx decreases until the equivalence ratio of 1.8 and thermal NOx increases between the equivalence ratios of 1.0 and 1.8. However NOx concentration decreases quickly below the stoichiometric condition. The use of swirl is effective for the reduction of flashback and the extention of the flammability limit to near 0.5.



Fig.5 Flamability limit



There are four types for the shape of methane premixed swirl burner flame (Fig. 7). Type I is the flame formed outside the burner rim. Type II is the compound of two flames; one held by swirl blades and another held by the hollow center nozzle. Type III is the separated flames; one held by swirl blades and another held by the hollow center nozzle. Type IV is the flame held by the inner rim and the hollow center nozzle.



Fig.7 Four types of flames at Swirler Angle of 30 degrees (Schlieren pictures)

OH profiles in flames are studied using PLIF system. Figure 8 shows the combustion intensity and that Type III and IV flame has a strong intensity at the swirl blade neighbors. PLIF images show the clear hollow structures of flames. The effects of swirl blades are significant for high Reynoldes number flow.



Fig.8 Four types of flames at Swirler Angle 30 (OH-PLIF pictures)

5.1.2 Methane premixed swirl burner flame with combustion chamber

The combustion chamber provides a fluctuation to flame. Schlieren photos are taken to see the flame structure and behavior and microphone is used to measure noise levels. Two-mode oscillatory

combustion is obtained at the swirl angle of 15 degrees (Fig. 8); one is the stable combustion where the flame moves back and force between the inner and outer rims and another one is the flame oscillates in the whole combustion chamber. The latter is unstable and will be blown off with more air-flow rate. When it is stable, the noise comes out due to the interaction with the nozzle rim.



Fig. 8 Two osicillatory combustions

Figure 9 shows the flame behavior with the swirl at the swirl angle of 30 degrees. The noise level of this flame is the highest at the air flow rate of about 30 l/min and oscillates at 125 and 155 Hz. Near the stoichiometric condition, the flame is stable since the stable combustion suppresses the oscillatory combustion. At the condition of air flow more than 50 l/min, there is no high noise since there is no interaction near the nozzle throat.



Fig.9 Change of the flame form by the increase in air flow rate at swirler

Figure 10 shows the high speed photos of oscillating flame. The oscillation period is 8 [ms] from the photos and its frequency corresponds to 125 [Hz]. For different swirl angles and air flow rates the flame frequencies of large noise are 125 and 150 [Hz]. These information becomes important when stabilizing the flames.



Fig.10 oscillation cycle CH4 4[l/min] Air 30 [l/min] with swirler Angle 30

5.2 Combustion Control by Mass Flow

A fundamental oscillation combustion control is applied using a noise meter as a sensor, putting them in to the PC memory by dSPACE board and changing them to flow rate signals to control actuator. The mass flow meter is this actuator to provide the air into the low noise region of combustion chamber. The flame shape changing from the time interval of 0 to 3.0 [sec]. The flame is held by the methane flow rate of 4 [l/min] and air of 30 [l/min]. The control starts when the noise becomes 70 [dB] or higher. When the noise becomes less than 70 [dB], the control signal keeps the air flow constant. Figure 11 is the case that methane flow rate is 4 [l/min] and air 30 [l/min] and Fig. 12 is the case that methane flow rate is 4 [l/min] and air 45 [l/min]. Both cases become stable, but with different reasons. The case of air flow rate 30 [l/min] moves to the complete combustion region and that of 45 [l/min] moves the flame mode where there is no interaction at the nozzle exit.





5.3 Combustion Control by Speaker

Primary oscillation frequency of the noise from this combustion at the condition of swirl angle 30° in Table1 is about 120Hz. When the sound pressure with the same frequency as of 120Hz is injected to near the flame swirled, the flame oscillation becomes harder and more unstable. This causes independently from the location of speaker, phase of sinusoidal wave, and so on. When the sound wave pressure of 60~70Hz, which is about the half of the primary frequency of the noise, is injected into the combustion flame region, the combustion oscillation is suppressed. This shows there exists the generation factor of this combustion oscillation near 60~70Hz of noise frequency. It seems that this low frequency phenomena cause the high frequency combustion oscillation of 120Hz. The frequency of 60~70Hz is not constant and varies by changing the combustion oscillation frequency due to the experimental condition. Hence 60~70Hz mode is the system eigen characteristic for the combustion. In other words there is a linear characteristic to some input. In the present situation the input may by the variation of flow rate, the mixture change, the velocity at the swirl exit, etc. The identification of the control system with the output can be performed by observing the half of the primary component using a low-pass filter. The future work will be to construct a closed loop control system after understanding the physical meaning of the low frequency, which is the half of the primary combustion oscillation mode, and selecting the better sensor and actuator. The total system, in this case, needs a model consisting of probability distribution of the unstable combustion factors.

6. Summery

Methane premixed burner flame and methane premixed chamber combustion are studied to develop a control system for unstable situations. The following are developed and found:

- (1) In the present system methane premixed burner has flammability limits based on the methane flow rates..
- (2) There are four types of flames are found in the system.
- (3) Methane premixed chamber combustion has oscillation and noises depending on the several frequencies.

- (4) The frequency suppresses the primary noise is the half of the primary frequency and the reason will come from the burner and chamber configuration.
- (5) The mass flow control system worked well as well as the speaker control system.

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The first part to construct a controlling system for methane lean premixed combustion system was achieved. The next step is to set up the closed control system for this combustor. The control function will be obtained through these fundamental study of the flames.

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