Combustion Instability Analysis in a Subscale Rocket Chamber with a Single Injector and Two Injectors

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Abstracts

Combustion instabilities of a subscale rocket combustor mounted with gas-centered swirl coaxial (GCSC) injectors are investigated numerically and experimentally. The boundary conditions are divided into two conditions for propellants injection: fuel-lean and fuel-rich. When only single injector is installed on the combustor, stability enhances firstly and then degrades as the equivalence ratio increases from fuel-lean to fuel-rich condition. It means that when the equivalent ratio gets close to the stoichiometric value, the combustion in the combustor becomes stable, and when the equivalent ratio becomes a very small or large value, the combustion becomes unstable. When two injectors are installed on the combustor, effects of injector gap on combustion instability are studied numerically. When the injector gap is small, the local equivalence ratio between two injectors becomes larger. Therefore, stability degrades in the fuel-rich cases and enhances in the fuel-lean cases. When the injector gap becomes larger, the local equivalence ratio between two injectors decreases. Then, stabilities in fuel-rich and fuel-lean cases enhance and degrade, respectively.

1 Introduction

The combustion instability has been one of the most challenging issues in the rocket engine combustion. It has been extensively studied during the past decades, and findings have been reported in the various literatures [1, 2]. Until now, the prediction of combustion stabilities is still one of the most difficult tasks in the development process of a new rocket engine. Lots of previous studies show that the injector is one of the key elements and has a great impact on combustion instability [3, 4]. And, gas-centered swirl coaxial (GCSC) injector is typically used in a liquid rocket engine adopting the staged combustion cycle [5]. Consequently, study on the impact of the GCSC injector on combustion instabilities of the rocket combustor is required with a top priority.

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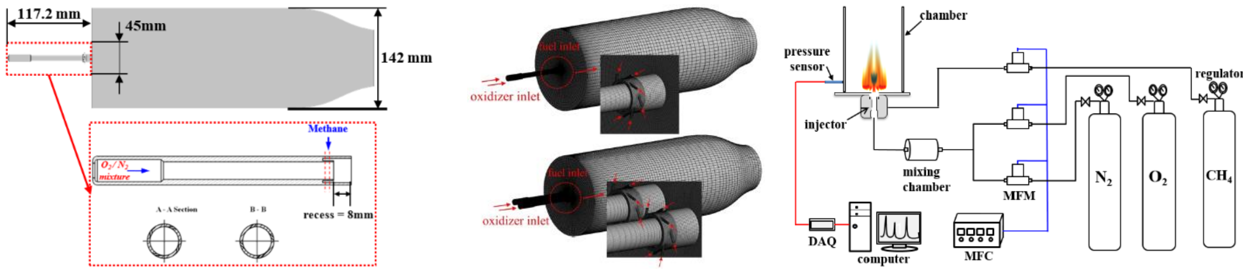

Figure 1. Left: geometry of a GCSC injector and a combustor; middle: grids; right: experimental apparatus

In literatures, many studies have been carried out for the purpose of analyzing the effect of GCSC injector on the combustion instability in the combustor, and a scaling method was established on the basis of hydraulic similarity [6]. This scaling method can be used to calculate the boundary conditions for numerical simulations and experiments based on the actual conditions. By using this method, the spray pattern, injection, and combustion properties were investigated with gas-gas injection through the GCSC injector [7, 8, 9].

In the present study, the effect of various boundary conditions on combustion instabilities of a subscale rocket combustor with a single injector is analyzed numerically and experimentally. However, in actual rocket engines, hundreds of injectors are usually installed in the combustor. Therefore, it is not enough to consider single injector only. For more complete understanding of combustion instability, the interaction between injectors must be taken into account. In this regard, instabilities of combustor with two injectors are studied in this work. Effects of injector gap on combustion instabilities are examined.

2 Numerical model and experimental setup

The geometry and grids of a subscale combustor with a single and two injectors are seen in Fig. 1. The injector and combustor models are the same as those in our previous study [7]. The gas-phase oxidizer is injected axially through the center while the fuel is tangentially injected through 8 holes in the A-A and B-B cross sections of the injector. A-A and B-B plane indicate the fuel inlet location. After injection, fuel and oxidizer will be mixed in the recess part with a length of 8 mm. In this study, hybrid mesh grids are adopted and the number of grids for a single and two injectors are approximately 530,000 and 1,200,000, respectively.

Table 1: Boundary conditions of fuel-rich and fuel-lean cases for experiments and numerical simulations.

	Fuel-rich cases			Fuel-lean cases			
Test No.	1	2	3	4	5	6	7
Fuel $\dot{Q}$ [LPM]	10			5			
Oxidizer $\dot{Q}$ [LPM]	34	40	57	40	50	70	75
MFR	8	12	23	49	74	140	160
Equivelence ratio	1.98	1.61	1.17	0.80	0.65	0.47	0.44

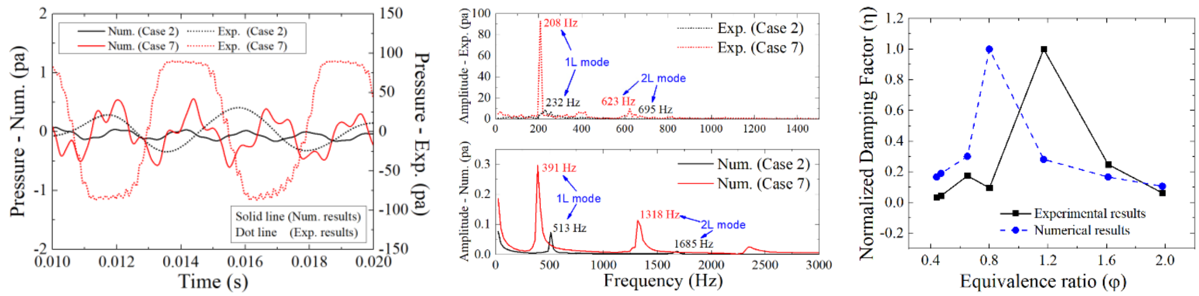

Figure 2. Left: Pressure signal of case 2 (operating condition) and case 7 (relative unstable condition); middle: FFT results of case 2 (operating condition) and case 7 (relative unstable condition); right: damping factor variation in single-injector cases as a function of equivalence ratio (square symbols: experiments, circular symbols: numerical simulations)

The oxidizer is a mixture of 33% oxygen and 67% nitrogen in terms of mole fraction and the fuel is methane. Boundary conditions are determined by applying the scaling method, which was suggested in the previous work [6, 7]. The key point of applying the scaling method is to maintain hydrodynamic similarity between the model and the actual rocket conditions. In this regard, the momentum flux ratio (MFR) is selected to represent hydrodynamic similarity [6, 7]. The MFR parameter is defined as

$$MFR = \frac{\rho_o U_o^2}{\rho_f U_f^2}, \tag{1}$$

where the subscripts, *o* and *f*, indicate oxidizer and fuel, respectively. And ρ and *U* denote density and axial velocity, respectively. Boundary conditions for numerical simulations and experiments are listed in Table 1. They are divided into fuel-rich and fuel-lean conditions. The fuel volume flow rates for the fuel-rich and fuel-lean cases are fixed at 10 and 5 LPM, respectively. MFR and equivalence ratio vary by increasing the oxidizer flow rate. The case 2 for fuel-rich conditions has the same MFR of 12 as that for the actual operating boundary condition in a rocket engine.

Governing equations of continuity, momentum, energy, and species are solved to simulate flow characteristics by using a commercial CFD solver [10]. The Reynolds averaged Navier-Stokes (RANS) equations based on the k-ε equation are used to simulate turbulence flow. The injection pressure is 1 atm and flow is compressible. And GRI 3.0 mechanism for methane reaction is adopted and steady diffusion flamelet model is selected to simulate turbulence combustion [10].

The right figure in Fig. 1 shows a diagram of the experimental apparatus. Fuel and oxidizer are supplied and controlled by mass flow controller (MFC). The sound pressure level is measured by a microphone, which is mounted on the chamber wall, and recorded by the National Instruments DAQ card. The sampling frequency is 256 kHz.

3 Results and discussion

In all single-injector cases, the amount of fuel is fixed and the oxidizer flow rate is increased. Then, the amplitude of pressure fluctuation in the combustor tends to increase. This can be confirmed by pressure signals in both experiments and numerical simulations. Pressure signals of case 2 (operating condition) and case 7 (relative unstable) are shown in Fig. 2. Obviously, the fluctuation of case 7 with larger oxidizer flow rate is higher than case 2. Pressure fluctuation amplitudes are found as a results of FFT as shown in the middle of Fig. 2. By adopting theoretical acoustic wave calculation, frequencies of longitudinal modes can be confirmed and marked in the figure. Frequency differences between experimental and numerical results come from the different combustor temperature. The numerical simulation shows over-estimation of the temperature. Relative stability is evaluated by the parameter of damping factor in this study. The parameter is defined as the following equation [11],

$$Damping\ factor\ \eta = \frac{f_2 - f_1}{f_{peak}}, \tag{2}$$

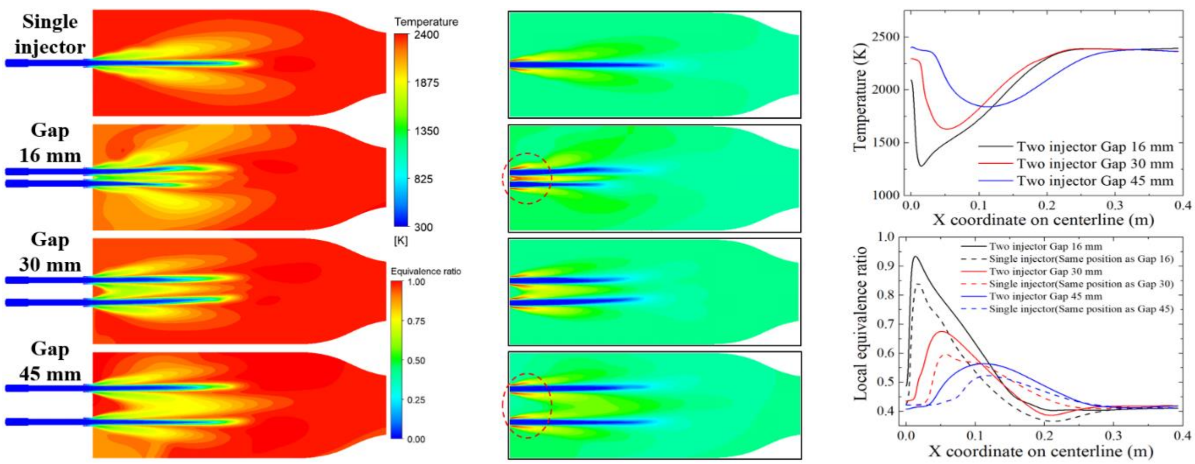

Figure 3. Left: Temperature fields of single injector case and two injector cases with different gaps (Case 1); middle: equivalence ratio fields of single injector and two injector cases (Case 1); right: temperature and local equivalence ratio profiles along the centerline with three injector gaps, local equivalence ratios are compared between single injector and two injectors.

where f_{peak} is the target frequency, f_1 and f_2 are the frequencies which have the value of $P_{peak}/\sqrt{2}$, and P_{peak} is the value of the amplitude corresponding to f_{peak}. Small damping factor indicates sharp peak, leading to strong resonance or unstable combustion.

In the present study, the frequency of the second longitudinal (2L) mode is selected as the target frequency. All of the damping factors mentioned here are obtained for 2L mode. In order to examine relative instability in each case, damping factors are obtained from experiments and numerical simulations and are shown in the right part of Fig. 2. It can be seen that as the equivalence ratio increases, damping factor in single-injector cases increases firstly and then, decreases. Experimental results qualitatively agree with the numerical results, but some quantitative error can be seen, which should be improved in our future studies. Results show that the most stable region has equivalence ratio between 0.8 and 1.2. In other words, when the equivalence ratio gets close to the stoichiometric ratio, the chamber exhibits stable burning. This result provides a valuable reference for selecting the conditions of the injector in terms of combustion stability.

Next, combustion instability in two-injector cases is investigated numerically. The gaps between two injectors are selected as 16, 30, and 45 mm. Two fuel-rich cases, i.e., cases 1 and 2, and two fuel-lean cases, i.e., cases 6 and 7, are selected for numerical simulations. In case 1, for example, temperature fields and equivalence ratio fields in both the single-injector and the two-injector cases are shown in Fig. 3. From the left figure in Fig. 3, it is seen that the temperature field in the single-injector case shows a symmetric flame shape with a steady state. When another injector is added with a gap of 16 mm, flame becomes asymmetrical and unstable, which is caused by the small injector gap and the same swirl direction of two injectors. As the injector gap increases, the symmetric flame shape appears again with a stable state.

It is seen from the distribution of equivalence ratio in Fig. 3 that the local equivalence ratio between the two injectors is higher than other areas when the injector gap has a small value of 16 mm and larger than the local equivalence ratio of single injector case in the same position. According to the findings in single injector cases, if the equivalence ratio increases, damping factor in the fuel-rich case decreases and in the fuel-lean cases increases. As shown in Fig. 4, cases 1 and 2 are two fuel-rich cases that exhibit lower stability than in the single-injector case when the injector gap is 16 mm. As the injector gap increases, the local equivalence ratio in the region between two injectors decreases, and the stability of the fuel-rich case enhances. Conversely, when the injector gap is small, the increase in local equivalence ratio leads to enhanced stability in cases 6 and 7 which are two fuel-lean cases. And as the injector spacing becomes larger, the stability is degraded again.

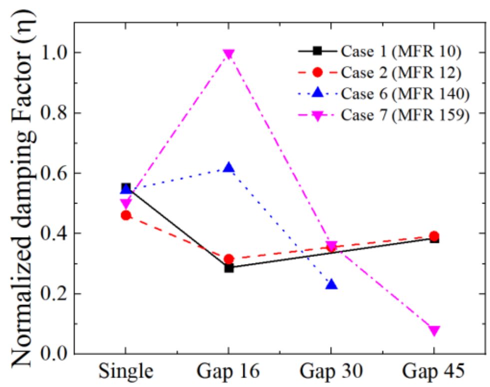

Figure 4. Damping factors in the single-injector and two-injector cases for fuel-rich boundary conditions (Cases 1 and 2) and fuel-lean boundary conditions (Cases 6 and 7)

From the above results, it is seen that although only one injector is added, the stability trend in two injector cases is different depending on boundary conditions or equivalence ratio. Therefore, these effects induced by interaction between multiple injectors on the combustion stability in the combustor should be considered in the chamber design of rocket engines.

4 Conclusion

In the present study, combustion instabilities of a subscale rocket combustor mounted with gas-centered swirl coaxial (GCSC) injectors are investigated numerically and experimentally. In single-injector cases, stability enhances firstly and then, is degraded with equivalence ratio changing from fuel-lean to fuel-rich conditions. When the value of equivalence ratio is close to unity, i.e., the stoichiometric ratio, the combustion becomes relatively stable. Effects of injector gap on combustion stability is studied numerically by changing injector gap between two injectors. When the injector gap is small, the local equivalence ratio in the region between two injectors becomes higher than unity. Therefore, stability will be degraded in the fuel-rich cases and will enhance in the fuel-lean cases. As the injector gap increases, combustion stabilities in fuel-rich and fuel-lean cases will be enhanced and degraded, respectively. It is because the local equivalence ratio in the region between two injectors is reduced. Effects of interaction between multiple injectors on combustion stability in the chamber are appreciable and must be considered in the chamber design of rocket engines.

Acknowledgments

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