Stability Characteristics of Bi-swirl Coaxial Injectors in Fuel-rich Combustion

By Kyubok AHN,1) Byoungjik LIM2) and Hwan-Seok CHOI2)

1) School of Mechanical Engineering, Chungbuk National University, Cheongju, Korea
2) Combustion Chamber Department, Korea Aerospace Research Institute, Daejeon, Korea

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Combustion stability characteristics in a small-scale combustor with seven liquid-liquid bi-swirl coaxial injectors were studied experimentally. Liquid oxygen and kerosene (Jet A-1) were burned in a fuel-rich combustor simulating a liquid rocket engine gas generator. While changing mixture ratios between 0.286 and 0.370, static pressure, temperature, and dynamic pressure data in the propellant manifolds and combustion chamber were acquired. In addition, chamber pressures were varied between 47.9 bar and 69.0 bar, which covered the sub- and supercritical pressures of oxygen. When the chamber pressure was above the critical pressure of oxygen, dominant pressure waves were not encountered. However, when the chamber pressure was below the critical pressure of oxygen, low-frequency pressure oscillations were found to develop in the manifolds and combustion chamber. Additionally, the amplitude of such low-frequency pressure oscillations increased as the pressure drop across the fuel-side injector was reduced. Accordingly, the effects of chamber pressure and pressure drop across the injectors must be carefully considered when designing a swirl coaxial injector operating in fuel-rich conditions.

Key Words: Swirl Coaxial Injector, Fuel-rich Combustion, Combustion Stability Characteristics, Chamber Pressure, Mixture Ratio

1. Introduction

In a pressure swirl atomizer, the liquid is fed into a swirl chamber through tangential holes or helical passages that give it a high angular momentum. On leaving the nozzle, the liquid spreads out in the form of a conical sheet due to the action of centrifugal force. Then, the liquid sheet disintegrates into ligaments and drops.1) Up to now, much research has been performed on pressure swirl injectors concentrating on discharge coefficient, spray cone angle, film thickness, drop size, breakup length, and dynamics according to injector geometry, injection pressure drop, ambient pressure, etc.2–8)

Bi-swirl coaxial injectors that discharge liquid oxygen (LOx) and kerosene have been primarily adopted in Russian rocket engines employing a gas generator cycle, such as the RD-0110 and RD-107/108. The swirl coaxial injector consists of two pressure-swirl atomizers with tangential holes in each swirl chamber and shows high mixing efficiency within a given length of the combustion chamber. Two conical liquid sheets may meet inside or outside the injector according to the spray cone angles and the recess length between the oxidizer injector post tip and the fuel nozzle tip.9) Sivakumar and Raghunandan10,11) found that the merging of liquid sheets increased the mean diameter of the global spray and identified various flow regimes of merged liquid sheet under different conditions. The spray characteristics of a liquid-liquid swirl coaxial injector such as droplet velocity and Sauter mean diameter (SMD) were studied by Soltani et al.12) They indicated that the inner injector had a larger influence on the flow field of the combined spray than the outer one. Investigating the spray characteristics with regard to recess length and ambient pressure, Kim13) revealed that the combined spray is affected by impingement conditions and momentum balance between the two liquid sheets.

According to other literature, some swirl coaxial injectors are vulnerable to longitudinal-mode combustion instabilities when used in the fuel-rich combustion of gas generator-like combustors.14) The recess in the swirl coaxial injector played an important role in influencing the interaction of propellants in the initial section of the chamber and also the pressure oscillations in the chamber.15) A larger recess length generally improved combustion performance in uni-element and multi-element combustors.16) In contrast, an increase in recess length deteriorated combustion stability and triggered low-frequency pressure fluctuations.17) Low-frequency pressure oscillations were attenuated inversely by increasing the chamber pressure in the thrust chamber-like combustor with mixture ratios around 2.7718) and the gas generator-like combustor with mixture ratios around 0.32,17) which were composed of swirl coaxial injectors using LOx and kerosene. Some researchers have also observed low-frequency and high-frequency oscillations in liquid sheets while using swirl injectors.19,20) Although numerous cold flow tests and combustion tests were previously performed, a parametric study focusing on chamber pressure and mixture ratio in a multi-element combustor consisting of LOx-kerosene swirl coaxial injectors and operating in fuel-rich conditions is hard to find in the open literature.

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Therefore, the objectives of this study are 1) to understand the systematic effects of chamber pressure and mixture ratio on combustion stability in the multi-element combustor, and 2) to extend a similar type of investigation on the thrust chamber-like combustor to fuel-rich combustion in the gas generator-like combustor. Chamber pressures were varied from 47.9 bar to 69.0 bar, which covered the sub- and supercritical pressures of oxygen. Combustion tests were also performed by changing oxidizer-to-fuel mixture ratios between 0.286 and 0.370. The critical pressure of oxygen ($P_{CR,O}$) and that of kerosene (Jet A-1) are 50.4 bar and 23.3 bar, respectively.

### 2. Experimental Methods

#### 2.1. Bi-swirl coaxial injector and combustor

The schematic of the present liquid-liquid swirl coaxial injector is presented in Fig. 1. Similar to previous swirl coaxial injectors, LOx flows into the swirling chamber through six tangential holes, forms a swirl motion, and passes through the inner post into the combustion chamber. Kerosene (Jet A-1) is also supplied into the outer nozzle via six tangential holes, swirls down, and is discharged into the chamber. Since the recess number of the present injector is greater than unity (i.e., the LOx film impinges against the kerosene film inside the outer fuel nozzle), the injector has internal mixing characteristics. The calculated film thickness and swirl angle for LOx/kerosene are 0.48/0.93 mm and 80/96 degrees, respectively. The momentum flux ratio of LOx to kerosene at the nominal operating condition is 0.39, which is based on the calculated axial velocities. The recess length is 4 mm and the recess number is estimated to be 1.24. As shown in Fig. 1, the diameters of the inner post and the outer nozzle are 3.3 mm and 8.75 mm, respectively.

The multi-element combustor consists of an injector head, a combustion chamber, and a choked nozzle, as illustrated in Fig. 2. The injector head has seven identical swirl coaxial injectors, which are distributed uniformly along one concentric circle: one is located at the center and six on the first row. Liquid oxygen is supplied into the oxidizer manifold through one central tube at the oxidizer dome. Kerosene is fed into the fuel manifold via two symmetrically-installed tubes. The internal diameter of the cylindrical chamber is 74 mm and its length is 146 mm. The length from the faceplate to the nozzle throat is 252.4 mm and the throat diameter is 20.8 mm. The chamber and nozzle are made of stainless steel and have no cooling system since the combustion temperature is approximately 900 K. All of the parts are bolted together and sealed with inserted copper gaskets.

#### 2.2. Experimental conditions

Static pressure, temperature, and dynamic pressure data in the propellant manifolds and combustion chamber were acquired during hot-firing tests. Static pressure and temperature were recorded at 1,000 Hz using a data acquisition system (National Instrument, PCI). Pressure fluctuation was simultaneously sampled at 50 kHz using a high-frequency data acquisition system (Nicolet Instrument Technologies, Odyssey). A helium-bleed, water-cooled piezoelectric dynamic pressure sensor (PCB Piezotronics, 123A24) was flush-mounted on the chamber wall at 62 mm downstream from the injector faceplate. Pressure fluctuations in the oxidizer manifold and the fuel manifold were measured using a piezoelectric sensor (PCB Piezotronics, 102A11) and a piezoelectric sensor (PCB Piezotronics, 101A04), respectively. They were also flush-mounted on the oxidizer dome cover and the fuel ring cover. Each propellant flow rate was gauged by two volume flow meters (Hoffer) and one mass flow meter (Micro Motion) installed on each propellant supply line. Pressure and mass flow rate measurement uncertainties were confirmed to be less than 0.25% in the area of interest.

While systematically changing chamber pressure and mixture ratio, nine hot-firing tests were conducted without any damage to the hardware. The measured test conditions such as chamber pressure ($P_C$), oxidizer-side pressure drop across the injector ($\Delta P_{O}$), fuel-side pressure drop ($\Delta P_F$), LOx temperature in the oxidizer manifold ($T_O$), kerosene temperature in the fuel manifold ($T_F$), ratio of oxidizer mass flow rate to fuel rate ($OFR$), and total mass flow rate ($m$) are summarized in Table 1. To be more specific, TN6-1 and TN6-2 in Table 1 mean the data acquired during the sixth hot-firing test, which was separately calculated from the data sets corresponding to the different time intervals. This will be explained in detail in the next chapter.
3. Results and Discussion

3.1. Combustion test

The propellants were supplied to the combustor from LOx and kerosene run tanks pressurized by gaseous nitrogen. A preset programmable logic controller (Allen Bradley) automatically controlled the valve sequences. Ignition was achieved with a gaseous oxygen/gaseous methane torch igniter. Combustion usually lasted for 4 s, which was enough to obtain data in the steady-state condition for comparison of combustion performance and stability. For controlling mass flow rates, orifices were located ahead of the final valves in the supply lines.

Typical static pressure, raw dynamic pressure, and filtered pressure fluctuation data for the TN7 test are shown in Fig. 3. The time histories of pressure in the chamber (\(P_C\)), pressure in the oxidizer manifold (\(P_O\)), and pressure in the fuel manifold (\(P_F\)) are plotted in Fig. 3(a). Additionally, the time histories of their pressure fluctuations (\(P'_C\), \(P'_O\), \(P'_F\)) are depicted in Fig. 3(b). A close look at Figs. 3(a) and 3(b) shows some changes in combustion phenomena around 3.4 s. Chamber pressure grows slightly and its pressure fluctuation increases noticeably. The time intervals for data analysis are indicated by arrow-markers. For static pressure, temperature, and propellant flow rate, two time intervals were separately used as shown in Fig. 3(a). In the case of the TN7 test, for example, TN7-1 is the data obtained in the former time interval and TN7-2 is that in the latter time interval. When low-frequency pressure oscillations did not take place, dynamic pressure data was analyzed only from the latter time interval since pressure fluctuation data in the former time interval was only slightly different from that in the latter. Raw dynamic pressure data was digitally filtered by a band-pass of 30 and 10,000 Hz to eliminate direct current components and noise. The band-pass filtered pressure fluctuation data for TN7-1 and TN7-2 is displayed in Figs. 3(c) and 3(d). Non-harmonic pressure waves with small amplitudes (Fig. 3(c)) are found to have developed into harmonic pressure oscillations with sustained peak-to-peak pressure oscillations over 15% of the mean chamber pressure (Fig. 3(d)).

The measured test conditions are depicted in Fig. 4(a) in terms of chamber pressure and \(OFR\), where a square (□) means the data in the former time interval and a triangle (▲) indicates the data in the latter time interval sometimes with low-frequency pressure oscillations. The first three hot-firing tests (TN1–TN3) were conducted varying \(OFR\) at a nearly fixed chamber pressure of 59 bar above the crit-
ical pressure of oxygen. The next three tests (TN4–TN6) were performed changing the chamber pressure at a fixed OFR of 0.32. In the case of the TN6 test with the chamber pressure around 49 bar, low-frequency pressure oscillations occurred in the manifolds and combustion chamber. Thus, three more combustion tests (TN7–TN9) were carried out varying OFR at a fixed chamber pressure of 49 bar below the critical pressure of oxygen, as explained in Table 1. During the last three tests, low-frequency pressure oscillations were always found in the chamber. As combustion proceeded, both the chamber pressure and OFR increased slightly, as shown in Fig. 4(a), because of the change in LOx injection temperature or manifold/injector wall temperature during the start-up transient.

Discharge coefficients across the injectors under hot-firing tests were calculated and are presented in Fig. 4(b). Though the mass flow meter gives the LOx density data in the supply line, its value is always higher than that in the oxidizer manifold. Thus, oxygen densities which were calculated from the oxygen pressure and temperature measured in the oxidizer manifold were used to calculate discharge coefficients across the oxidizer injectors. When low-frequency pressure oscillations are encountered, discharge coefficients across the oxidizer injectors grow by approximately 10%, but those across the fuel injectors seldom change. As the flame location is moved downstream, the low-frequency pressure oscillations are assumed to weaken the so-called barrier effect in the recess region generated due to flame holding in the fuel nozzle injector. However, this assumption has not yet been confirmed. More quantitative research is required in the future to explain the phenomenon.

Characteristic velocity was calculated using static chamber pressure, nozzle throat area, and total propellant mass flow rate. Ideal characteristic velocity was also obtained using the Chemical Equilibrium Analysis (CEA) code. The calculated characteristic velocity efficiencies are plotted as a function of OFR in Fig. 4(c). As expected from previous research, the characteristic velocity and its efficiency have an approximately linear relationship with the mixture ratio, but are not a strong function of chamber pressure under the present test conditions. As combustion proceeded, the characteristic velocity efficiency went up due to the increase in OFR during the start-up transient.

3.2. Combustion stability

Combustion stability in a liquid rocket engine has been reviewed in much literature. Klem and Fry reported that, from the standpoint of combustion instability, an engine should operate without sustained peak-to-peak pressure oscillations over 10% of the mean chamber pressure. Raw pressure fluctuation data sampled at 50 kHz was digitally filtered by band-passes of 30 and 10,000 Hz. Using fast Fourier transform analysis, the power spectral density was calculated from the filtered pressure fluctuation data at 0.5 s, 25,000 samples, as shown in Fig. 3(b). Sampling frequency, number of points in the Fourier transforms, and number of blocks used in the ensemble average are 50 kHz, 16,384, and 8, respectively.

As written previously, when low-frequency pressure oscillations did not take place, dynamic pressure data was analyzed only from the latter time interval. Thus, TN8 (TN1, TN2, TN3, TN4, TN5) in this chapter means TN#-2 in Fig. 3(b). The power spectral densities of the filtered pressure fluctuations in the combustion chamber acquired from the first three hot-firing tests (TN1–TN3) with chamber pressures of around 59 bar are presented in Fig. 5. The test conditions for TN1 are similar to those for TN5, which will be discussed later, and thus the power spectral density of TN1 is not included in Fig. 5. Since the mixture ratio in TN3 is 23% larger than that in TN2, the combustion temperature and sonic velocity in the chamber can be expected to have been relatively higher. This can explain the shift of resonant mode frequencies. At the nominal OFR of 0.32, the acoustic mode frequencies in the combustion chamber are estimated as $1L = 1,268 \text{ Hz}$, $2L = 2,536 \text{ Hz}$, $1T = 5,068 \text{ Hz}$, $1T1L = 5,224 \text{ Hz}$, $1T2L = 5,667 \text{ Hz}$, $2T = 8,407 \text{ Hz}$, $2T1L = 8,502 \text{ Hz}$, and $2T2L = 8,781 \text{ Hz}$ based on the speed of sound obtained by Ahn et al. It was confirmed that there were no strong pressure oscillations and the operations were stable.

The power spectral densities in the combustion chamber measured from the next three hot-firing tests (TN4–TN6) with OFR in the vicinity of 0.32 are plotted in Fig. 6. The
results of TN4 and TN5 are similar to those of the previous tests (TN1–TN3), but the power spectral density in TN6 shows that there were two distinguishable combustion phenomena. The power spectral density of TN6-1 is almost the same as that of TN5. However, when low-frequency pressure oscillations start to sustain, the dominant peak around 150 Hz grows sharply and the power spectrum in the frequency range greater than 1,000 Hz drops slightly, as shown in Fig. 6(d).

The power spectral densities of the filtered pressure fluctuations in the combustion chamber obtained from the last three hot-firing tests (TN7–TN9) with chamber pressures of around 49 bar are displayed in Fig. 7. To better show the data in the low-frequency range, it is plotted logarithmically. When low-frequency pressure oscillations are encountered, the power spectral densities in the frequency range over 1,000 Hz always drop. The low-frequency peaks in the vicinity of 150 Hz increase sharply and their harmonic frequencies around 300 Hz can be seen, except for TN8-2. In the case of TN8-2, there are four small peaks in the frequency range below 300 Hz instead of one dominant peak.

The maximum peak power spectral density and its corresponding peak frequency for each combustion test as a function of the chamber pressure normalized by the critical pressure of oxygen are plotted in Fig. 8. Without low-frequency pressure oscillations, the maximum peak power spectral densities are always less than $10^{-2}$ bar$^2$/Hz. When the chamber pressure is below the critical pressure of oxygen and a strong low-frequency pressure fluctuation occurs, the maximum peak power spectral density grows to 0.5 bar$^2$/Hz. As the chamber pressure increases above $P_{CR,O}$, the maximum peak value seems to grow gradually. In addition, as the chamber pressure drops below $P_{CR,O}$, the peak value rises high or is only slightly changed depending on whether or not low-frequency pressure oscillations occurred. This tendency is analogous to the results in the shear coaxial injector using LOx and gaseous hydrogen, where, as the chamber pressure approached the critical pressure of oxygen, the peak-to-peak pressure oscillations became minimal. In the case of $P_{C}/P_{CR,O} > 1$, the maximum peak frequencies are found to be around 9,000 Hz. However, in the case of $P_{C}/P_{CR,O} < 1$, the maximum peak frequencies exist in the low-frequency range below 200 Hz. In particular, when dominant low-frequency pressure oscillations develop, the maximum peak frequencies shift from 100 Hz to 150 Hz.

Root-mean-square (RMS) values of the previously filtered pressure fluctuations normalized by the chamber pressure are presented in Fig. 9, where $P_{C'}$, $P_{O'}$, and $P_{F'}$ are filtered pressure fluctuation data at the chamber, oxidizer...
manifold, and fuel manifold, respectively. Root-mean-square values can indicate the level of combustion roughness. Without low-frequency pressure oscillations, the RMS values of pressure fluctuations in the combustion chamber are around 2% of the chamber pressures and are not a strong function of chamber pressure. When low-frequency pressure oscillations take place, the RMS value of pressure fluctuations in the chamber grows to 5% of the chamber pressure (i.e., approximately 15% of the chamber pressure based on the peak-to-peak amplitude). Thus, it can be said that the combustions have become unstable from the viewpoint of Klem and Fry.\(^\text{24}\)

Figure 9(a) shows that, in the case of \(\frac{P_C}{P_{CR,O}} < 1\), LOx/kerosene combustion in fuel-rich conditions is vulnerable to low-frequency combustion instability. When comparing the RMS values in the propellant manifolds and chamber, while strong low-frequency pressure fluctuations take place, the values in the chamber match better with those in the fuel manifold than those in the oxidizer. For the TN5-2, TN7-2, and TN9-2 cases, the normalized RMS values at the chamber show an approximate 0.6% difference from those at the fuel manifold, but exhibit a 26.7% difference on average from those at the oxidizer manifold. Though not presented in this paper, at that time, the power spectral density in the chamber nearly coincided with that in the fuel manifold, but deviated slightly from that in the oxidizer manifold within the low-frequency range below 500Hz. The low-frequency pressure fluctuations in the chamber may be coupled more with the fuel feed system since fuel flow rate is three times larger than oxidizer flow rate. In the present combustor with the swirl axial injectors with internal mixing characteristics, the chamber pressure below the critical pressure of oxygen is thought to induce low-frequency pressure oscillations like in the thrust chamber-like combustor with bi-swirl coaxial injectors.\(^\text{30}\) The low-frequency pressure oscillations seem to be related to the oxygen phase injected into the combustion chamber, which is affected by the chamber pressure because the oxygen phase may significantly modify the combustion time delay in such fuel-rich conditions (i.e., surrounded by unburned hot vaporized kerosene).

The RMS values, normalized by the chamber pressure, of the filtered pressure fluctuations in the combustion chamber are displayed again as a function of injector pressure drop normalized by the chamber pressure, as shown in Fig. 10. When the oxidizer-side pressure drop across the injector is approximately less than 16% of the chamber pressure, the low-frequency pressure oscillations become dominant in the combustion chamber. The oxidizer-side pressure drop itself does not seem to affect the amplitude of the pressure fluctuations. In contrast, the fuel-side pressure drop across the injector is seen to be related to the amplitude of the pressure fluctuation. As the normalized fuel-side pressure drop decreases, the RMS values drop almost linearly in the cases without low-frequency pressure fluctuations. However, when low-frequency pressure oscillations take place, the RMS value rises steeply as the normalized fuel-side pressure drop slows. Under the present fuel-rich experimental conditions, the chamber pressure is almost directly connected to the fuel-side pressure drop since the flow rate is proportional to the root of the pressure drop. In summary, it is thought that the occurrence of the low-frequency pressure oscillations is determined by the chamber pressure associated with the injected oxygen phase rather than the oxidizer-side pressure drop, and then the amplitude of the pressure oscillations is affected by the fuel-side pressure drop due to the strong coupling between the chamber and the fuel-feed system.

Marchione et al.\(^\text{18}\) found that the spray fluctuated around 100–125 Hz in the hollow cone spray of the simplex nozzle, and this behavior could be induced by the swirl chamber in the injector. Kim\(^\text{13}\) found that impact waves could be generated by the impingement of two liquid sheets in the internal mixing injector, and reported that the merged surface wave fluctuated at around 200 Hz, which was much different from the measured wave frequencies of the individual liquid sheets. According to these findings, spray fluctuations due to the hydrodynamics of the swirl injector or the impact waves in the present study might excite heat release rate oscillations in the combustion chamber, which would be coupled with the propellant feed systems.\(^\text{9}\) Then, coupling would increase the amplitude of the pressure fluctuations as the fuel-side pressure drop slowed in the present study. For the case of low chamber pressure (\(\frac{P_C}{P_{CR,O}} < 1\)), the impact waves would be much stronger because LOx in the liquid-state collides with kerosene, as atomization and combustion of cryogenic propellants under subcritical/supercritical conditions have shown.\(^\text{26,27}\) This could explain the low-frequency pressure fluctuations with higher amplitudes under such conditions.

To better understand the low-frequency pressure oscillations, correlation coefficients between the pressure waves in the propellant manifolds and chamber were calculated and are presented in Fig. 11. While there are no low-frequency pressure oscillations, the correlation coefficients in Figs. 11(a) and 11(b) are less than 0.3. At that time, the correlation coefficients between the oxidizer manifold and the chamber seemed to be generally larger than those between the fuel manifold and the chamber. When low-frequency combustion instabilities were encountered, on the other hand, the correlation coefficients increased to over 0.7. Ad-
the chamber are shown in Fig. 12. In the case of frequencies with the maximum power spectral densities in manifolds and those in the combustion chamber at the peak coupling of the pressure waves between the chamber and the pressure drop across the fuel injectors affecting the chamber pressure relative to the critical pressure of oxygen as the low-frequency pressure oscillations start to develop. Under the present experimental conditions, it can be concluded that the low-frequency pressure oscillations turn into combustion instability with sustained peak-to-peak amplitude (i.e., 15% of the chamber pressure based on the peak-to-peak amplitude).

Comparing the RMS values and correlation coefficients between the pressure waves in the manifolds and chamber, spray fluctuations caused by the hydrodynamics of the swirl injector or the impact waves under the conditions of chamber pressure below the critical pressure of oxygen could excite heat release rate oscillations in the combustion chamber, causing the generated pressure waves to be more strongly coupled to the fuel-feed system.

From these results, when one designs a swirl coaxial injector for a gas generator operating in fuel-rich conditions, chamber pressure and injector pressure drop should be carefully considered for better combustion stability. In the future, swirl coaxial injectors in fuel-rich conditions with different geometries need to be studied to gain a deeper understanding and draw more general conclusions.

4. Conclusion

The effects of chamber pressure and mixture ratio on combustion characteristics in fuel-rich combustion were investigated experimentally using a multi-element combustor with seven LOx-kerosene swirl coaxial injectors. While simultaneously changing the chamber pressure from 47.9 bar to 69.0 bar and the mixture ratio from 0.286 to 0.370, the static pressure, temperature, pressure fluctuation, and mass flow rate data were obtained and analyzed.

The pressure fluctuation data shows that when the chamber pressure is above the critical pressure of oxygen, the RMS values normalized by chamber pressure are always below 2.5% in the combustion chamber. However, when the chamber pressure is below the critical pressure of oxygen, strong low-frequency oscillations in the vicinity of 150 Hz develop. Additionally, as the pressure drop across the fuel-side injectors decreases, their RMS values normalized by the chamber pressure grow to more than 5% of the chamber pressure.

From these results, when one designs a swirl coaxial injector for a gas generator operating in fuel-rich conditions, chamber pressure and injector pressure drop should be carefully considered for better combustion stability. In the future, swirl coaxial injectors in fuel-rich conditions with different geometries need to be studied to gain a deeper understanding and draw more general conclusions.

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