Experimental Study on the Unsteady Spray Combustion Process of a Liquid Oxygen/Methane Swirl Coaxial Injector

Pengjin Cao, Xiao Bai, Qinglian Li, Peng Cheng, and Ziguang Li

ABSTRACT: The present study experimentally investigated the dynamic spray combustion process of a liquid-centered swirl coaxial injector using liquid oxygen/methane in an optically accessible liquid rocket engine. Data were obtained at combustor pressures from 0.4 to 1.8 MPa and the ratio of the oxidizer mass flow rate to the fuel rate between 1.32 and 1.55. Liquid oxygen was injected at 120 K, and the injection temperature of gaseous methane was about 285 K. Based on the obtained spatial distribution and oscillation characteristics of liquid oxygen/methane flame, the combustion process was described by four subprocesses: ignition, low-frequency oscillation combustion, quasi-steady state combustion, and shutdown. In the quasi-steady state combustion subprocess, both the flame length and the normalized flame area are the largest, and the flame expansion angle is the smallest. At the initial stage of combustion, the instability of the liquid oxygen phase state leads to flame instability, which generates low-frequency unstable combustion with a dominant frequency of 93.74 Hz. In addition, the high-frequency (2500–3000 Hz) oscillation of the flame appeared in the whole combustion process. It has been confirmed to be caused by the self-pulsation of spray. Furthermore, with the increase in liquid oxygen manifold pressure, the liquid oxygen phase state changes from a two-phase mixture of liquid and gaseous oxygen to a liquid phase, which increases the mass flow rate of liquid oxygen entering into the combustor, thus generating the increase in the high oscillation frequency of the flame through the whole combustion process.

1. INTRODUCTION

Recently, liquid oxygen (LOx)/methane has been regarded as the better propellant combination for high-thrust liquid rocket engines. The LOx/methane liquid rocket engine is a potential propulsion for a reusable launch vehicle and heavy lift launch vehicle booster due to its desirable properties, such as high specific impulse, low cost, environmentally friendly performance, and reusability. As the critical component of liquid rocket engines, injectors greatly affect the atomization, evaporation, mixing, and combustion process of the propellant. Compared with gas–liquid coaxial shear injectors, gas–liquid swirl coaxial (GLSC) injectors have better atomization performance, higher combustion efficiency, and improved combustion stability.

Since the interaction between the conical liquid film formed by the swirl nozzle and the annular gas is highly complex, experimental observation and numerical simulation have been the main approaches to study the combustion characteristics of the GLSC injector. Jones et al. investigated the strong swirl spray combustion flow field using the large eddy simulation method and found that the spray center formed a large recirculation zone that was surrounded by the flame front. Xu et al. numerically studied the effects of injector structural parameters and injector number on the combustion performance of LOx/methane engine. Yu et al. established that the high propellant momentum ratio is not conducive to flame propagation by experimentally and numerically studying the effect of the fuel/oxidizer momentum ratio on the mixing and combustion performance of coaxial injectors. Salgues et al. compared the flame structures of LOx/methane shear coaxial injectors and swirl coaxial injectors using noncontact optical diagnostic technology. It was indicated that the flame expansion angle of swirl coaxial injectors is larger and the chemiluminescence region of OH is closer to the injection panel. Wang et al. reported that the flame was anchored in the center nozzle tip of the gas-centered swirl coaxial injector and further enhanced in the conical region downstream using the large eddy method. Guobiao et al. studied the effect of the ratio of the oxidizer mass flow rate to the fuel rate on the flame structure of swirl coaxial injectors using the OH-PLIF diagnostic technology.
technology and high-speed photography. It was shown that the flame of swirl coaxial injectors forms a recirculation zone at the central axis, which causes the return of a large amount of combustion products, and that the combustion zone mainly concentrates in the spray shear layer. Balance et al.16 experimentally observed the spray combustion characteristics of high-pressure combustors and found that the flame is tapered and approximately axisymmetric when the combustor pressure and propellant injection velocity are low. Dai et al.17 reported that the wall thickness of the inner LOx post can significantly affect the flame stability. Juniper et al.18 indicated that the flame is anchored at the tip of the inner LOx post when the combustor pressure is lower, and, on the contrary, the flame expansion angle decreases.

In general, the study on the combustion characteristics of gas–liquid swirl coaxial injectors is still relatively macroscopic, mainly analyzing and comparing the combustion performance and combustion stability of this kind of injectors, but there are few studies on the flame structure, flame stability mechanism, and flame dynamic characteristics of them. As swirl coaxial injector self-pulsation will occur under specific operating and structural parameters,19−21 the self-pulsation spray will lead to flame oscillation,22 which may in turn cause unstable combustion. Kawashima et al.23 established that the flame shows an annular vortex structure during unstable combustion. Therefore, the dynamic characteristics of flame must be given attention.

To date, many research studies have focused on the acoustic oscillation, heat release rate distribution, and flame dynamic characteristics of LOx/GCH4 and LOx/H2 combustion processes.24−26 Matsuyama et al.27 reported that the flame approaches and leaves the injection panel periodically when the propellant injection is coupled with the first-order oscillation mode of the combustor. Lux and Haidn28,29 showed that the flame characteristics of LOx/GCH4 and LOx/H2 are highly similar under the same operating conditions, and the flame expansion is enhanced after the inner post recesses. Worth and Dawson30 found that the fluctuation of the heat release rate and self-excited instability affects the extinguishing position of the flame. Song et al.31 studied the spray flame characteristics of gas-centered swirl coaxial injectors and reported that external excitation can excite unstable flames. Malbois et al.32 examined the swirl spray flame and confirmed that there are internal and external shear layers in the flame structure. Buschhagen et al.33 experimentally studied the self-excited combustion instability under high pressure lean jet and proved that the longitudinal combustion instability is related to the flame axisymmetric vortex shedding and the transverse combustion instability is related to the flame non-axisymmetric vortex shedding.

The dynamic characteristics of flame are crucial to the combustion process of a liquid rocket engine. However, systematic studies on the flame characteristics of the combustion process in a LOx/methane engine have been lacking. There are no relevant reports on the ignition and combustion process of LOx/methane. The flame spatial distribution of LOx/methane is unclear, and the phenomenon of flame oscillation has not been studied in detail. Therefore, in the present study, we investigated the flame dynamic process, flame spatial distribution, and flame oscillation characteristics of the LOx/methane engine from ignition to shutdown in detail. The engine was equipped with a GLSC injector fed with LOx and methane. Firing tests were conducted under extreme fuel-rich conditions. The instantaneous flame images were obtained by flame spontaneous emission imaging technology.

2. EXPERIMENTAL METHODS

2.1. Experimental Facilities. The experimental apparatus consisted of a propellant feed system, a model engine, an GLSC injector, an exhaust system, a pressure and flow measurement system, and a Photron Fastcam SA-X2 camera. LOx and methane were supplied through a pressurized feed system. High-pressure nitrogen was used to blow away the residual propellants in the LOx/methane manifold, combustor, and exhaust system for all tests, as shown in Figure 1.

Figure 1. Experiment system.
The pressures in the liquid and gas manifold as well as the combustor were measured by piezoresistive pressure sensors with an accuracy of 0.05 MPa. The temperatures in liquid and gas manifold were recorded by thermocouple temperature sensors with an accuracy of 0.25%. A single turbine flowmeter with an accuracy of 0.78 g/s was used to measure the volume flow rate of methane. The mass flow rate of LOx was detected by a mass flowmeter with an accuracy of 1.46 g/s. Signals from the pressure and temperature sensors were acquired synchronously using one National Instrument Acquisition System. The sampling rate of the measurement was 1 kHz, and 10 pressure sensors and three temperature sensors were included in total.

The test mode engine is composed of the GLSC injector manifold, one quartz glass window (16 × 5 cm) for optical access, a gaseous oxygen/liquid ethanol torch igniter, and an exhaust nozzle. The internal combustor is a cuboid with length, width, and height of 16 cm, 5 cm, and 5 cm, respectively, as plotted in Figure 2.

The schematic of the GLSC injector is shown in Figure 3. LOx flows into the swirling chamber through two tangential holes, forms a swirl motion, passes the oxidizer post, and is injected into the combustor. Methane is supplied to the fuel nozzle via an annular aperture, flows straight down, and interacts with LOx in the recess chamber. The key geometrical parameters of the injector are listed in Table 1.

### Table 1. Geometric Parameters of the GLSC Injector

| Parameter | Value |
|-----------|-------|
| \(D_1\) (mm) | 6.5 |
| \(L_1\) (mm) | 50 |
| \(D_{g,ir}\) (mm) | 9.1 |
| \(D_{g,or}\) (mm) | 12 |
| \(D_{f}\) (mm) | 15.2 |
| \(L_6\) (mm) | 13 |
| \(D_t\) (mm) | 2.2 |
| \(R_{sw}\) (mm) | 6.5 |
| \(\alpha\) (°) | 90 |
| \(L_5\) (mm) | 4 |

2.2. Experimental Conditions. Table 2 summarizes the test conditions, such as chamber pressure \((P_c)\), chamber temperature \((T_c)\), oxidizer-side pressure drop in the injector \((\Delta P_{o})\), fuel-side pressure drop \((\Delta P_{f})\), LOx temperature in the oxidizer manifold \((T_{o})\), methane temperature in the fuel manifold \((T_{f})\), ratio of the oxidizer mass flow rate to the fuel rate \((OFR)\), coefficient of residual oxygen \((\alpha)\), and total mass flow rate \((\dot{m})\). The results were acquired from three hot-firing tests for the LOx/methane engine while changing the chamber pressure and \(OFR\).

2.3. Experimental Techniques. A high-speed camera was employed to directly capture the instantaneous flame images with an exposure time of 17.5 µs, as depicted in Figure 2. The frame rate of the camera was 20,000 fps, and the physical resolution was about 0.165 mm/pixel.

The oscillation frequency of the flame, flame expansion angle, flame area, and flame length can be obtained by processing a series of instantaneous flame images. The image processing procedures for the measurement of the flame oscillation frequency are shown in Figure 4. First, raw images are transformed into grayscale images by choosing a suitable threshold. Second, the sum gray values are extracted for the flame images at a rectangular area (with a length of 2.5 \(D_{g,or}\) and widths of 0.5 \(D_{g,ir}\) and 0.7 \(D_{g,or}\) downstream of the injector exit and symmetrically distributed on both sides of the center line of the injector), where the flame patterns cover periodically. Third, the time series of gray values are obtained by applying these two steps to 2000 instantaneous flame images. Finally, the oscillation frequency of the flame can be acquired by the fast Fourier transform (FFT) algorithm of the obtained time series.

3. RESULTS AND DISCUSSION

3.1. Process of Operation. The propellants are supplied into the combustor by LOx run tanks constantly pressurized with high-pressure gaseous oxygen and high-pressure methane cylinders. A preset programmable logic controller automatically regulates the opening and closing sequences of all valves. The propellants injected into the combustor are ignited by a torch flame. To ensure that the LOx manifolds are adequately precooled, 50 s precoring time is set before ignition. The typical pressure data for Case2 are plotted in Figure 5. Combustion usually lasts for 1 s, which is sufficient to acquire data in the combustion process for combustion performance and stability. The amplitude of combustion chamber pressure...
is less than 5% average chamber pressure without dominant oscillation frequency, as described in Figure 6.

The propellant is pressurized from the run tank to the final valve before the firing tests, and a cavitating venture and sound speed nozzle are located ahead of two injector inlets, respectively. The opening of the valve momentarily supplies the propellant with higher pressure. The response time for the fuel control system is about 70 ms. The combustor pressure climbs rapidly and oscillates widely after fuel injection; the amplitude of chamber pressure oscillation changes constantly and finally becomes stable. Furthermore, based on the variation of the pressure oscillation amplitude of the combustor, the combustion process is divided into four combustion subprocesses: ignition, low-frequency oscillation combustion, quasi-steady state combustion, and shutdown, as shown in Figure 6.

3.1.1. Ignition Subprocess. After the methane valve is opened, the combustor pressure begins to rise with the chamber pressure oscillating; however, its oscillation amplitude gradually attenuates and the chamber pressure rises to 90% of

| test  | $\Delta P_r$ (MPa) | $\Delta P_f$ (MPa) | $T_r$ (K) | $T_f$ (K) | OFR | $\alpha$ | $P_i$ (MPa) | $T_i$ (K) | $L_r$ (mm) | $m$ (g/s) |
|-------|------------------|------------------|---------|---------|-----|---------|----------------|---------|---------|---------|
| Case1 | 0.53             | 0.3              | 127     | 287     | 1.32 | 0.33    | 1.01           | 1303    | 4       | 149.7   |
| Case2 | 0.58             | 0.3              | 125     | 286     | 1.48 | 0.37    | 1.11           | 1624    | 157.9   |
| Case3 | 0.66             | 0.3              | 122     | 284     | 1.55 | 0.39    | 1.16           | 1774    | 158.6   |

Table 2. Experimental Conditions for the LOx/Methane Engine

Figure 4. Image processing procedures for the measurement of oscillation frequency.

Figure 5. Typical pressure curve of the firing test.
the stable chamber pressure for a duration of 58 ms. Figure 7 demonstrates the evolution of a combustion flow field at different times during the ignition process of a LOx/methane engine, and Figure 8 shows the variation curve of the LOx/methane propellant mass flow rate and pressure drop during the combustion process.

The moment when the methane valve opens is \( t_0 \) (\( t_0 = 50.16 \) s). Before the engine is ignited, LOx is continuously injected into the combustor at a rated mass flow rate; therefore, the combustor is an oxygen-rich environment. The torch igniter starts to function (\( t_0 + 90 \) ms), and the torch flame heats part of the LOx such that it evaporates. With the injection of methane, it is rapidly mixed with gaseous oxygen and ignited by the torch flame. Subsequently, the propellants quickly react. A light blue flame gradually appears from the injection panel (\( t_0 + 95.6 \) ms) as fire starts in the combustor. Due to the low mass flow rate of methane into the combustor (Figure 8), the resulting weak flame has a slender shape. With the gradual decrease in methane pressure, the flame progressively brightens, develops into a conical shape, and then forms a larger recirculation zone at the moment of \( t_0 + 105.8 \) ms, which makes the flame stably adhere to the injection panel. Due to the instability of the gas−liquid interface, small vortices continually develop at the injector outlet, the combustion products separate at the wall of the combustor (\( t_0 + 117.1 \) ms), part of the combustion products enter the recirculation area near the injection panel, and the other portion of the combustion products enter the latter half of the combustor, making the vortices gradually dissipate.

3.1.2. Low-Frequency Oscillation Combustion Subprocess. The chamber pressure continually oscillates at low frequency; at first, its oscillation amplitude increases and then gradually attenuates to stabilize, which lasts for 295 ms. In this process, the flame shape of the combustor periodically changes. The process can be divided into two stages according to the oscillation amplitude of the chamber pressure. The first stage shows a gradual increase in the chamber pressure amplitude (i.e., amplitude rising stage), whereas the second stage exhibits a gradual decrease in the chamber pressure amplitude (i.e., amplitude decreasing stage). Figure 9 presents the flame structure for the oscillation period of the two stages. In the first half of the period, the flame shape of the amplitude decrease stage is close to the cone shape, while the amplitude rising stage is similar to the cloak shape. Halfway during the oscillation period, the combustion zone occupies most of the combustor in the amplitude rising stage and a large area of the edge combustion zone occurs. In the amplitude decreasing
stage, the combustion zone is mainly distributed on the central axis of the combustor with a small area of the edge combustion zone, which is beneficial for the thermal protection of the combustor.  

3.1.3. Quasi-Steady State Combustion Subprocess. The oscillation amplitude of the chamber pressure remains stable at 5% of the stable chamber pressure for a period of 557 ms. In this process, the pressure drop of LOx/methane and the combustor pressure are relatively constant, as shown in Figure 6 and Figure 8. Figure 10 plots the flame structure of this subprocess.

3.1.4. Shutdown Subprocess. The chamber pressure gradually decreases from a stable value to ambient pressure in a period of 600 ms. Figure 11 describes the flame structure during this process. The reaction intensity of the propellants decreases with the reduction of the fuel mass flow rate, as depicted in Figure 8. In addition, the weakening of the gas–liquid interaction causes the intense combustion zone to gradually develop toward the wall of the combustor, which triggers the appearance of the combustion hollow zone. This is due to the fact that the methane injection momentum decreases with the rise of LOx injection momentum, and methane is sucked to the outer edge of the flame by the vortices on the flame surface, as shown in Figure 12. Finally, the area of the combustion zone gradually decreases, and a large recirculation zone appears near the injection panel. This gradually decreases and oscillates with the drop of the LOx mass flow rate, the flame extinguishes completely, and the shutdown process is realized.

3.2. Flame Spatial Distribution. The spatial flame distribution in the combustion process of a liquid rocket engine mainly includes flame structures and flame characteristics. Figure 13 presents the changing trend of the flame expansion angle, flame length, and normalized flame area ($A_F/ A_C$). The flame expansion angle, flame length, and normalized flame area are all obtained from the time-averaged images of the flame structure. As depicted in Figure 13, the flame expansion angle increases in both the low-frequency oscillation combustion subprocess and the shutdown subprocess due to the increase in LOx momentum (Figure 12), but the momentum of methane shows little change. The decrease in the momentum flux ratio ($J = \rho_u u_f^2/\rho_f u_t^2$) leads to the increase in the spray cone angle of the GLSC injector, which in turn increases the flame expansion angle. The larger flame expansion angle makes the flame approach the wall of the combustor and the injector panel, which is not conducive to the continual operation of the engine.

Flame length is defined as the distance between the flame boundaries along the central axis of the combustor. The flame area is the area wrapped by the flame boundary. The normalized flame area is the ratio of flame area ($A_F$) to combustor area ($A_C$). During the combustion process of a LOx methane engine, both the flame length and normalized flame area first increase and then decline, and the flame length and normalized flame area reach their maximum in the quasi-steady state combustion subprocess, which are 69.7% of the
The combustion process is achieved by the temperature and phase change of LOx. The dryness change of LOx during the combustion process is carried out, as shown in Figure 16. The red curve represents the LOx density, thus affecting the mass flow rate of LOx into the combustor, as described in Figure 8, which eventually leads to unstable combustion. When the liquid oxygen dryness is unstable, the chamber pressure will show low-frequency instability, and the oscillation frequency of liquid oxygen dryness and chamber pressure are almost the same. On the contrary, the low-frequency instability of chamber pressure will disappear.

### 3.3. Oscillation Characteristics of Flame

#### 3.3.1. Low-Frequency Flame Oscillation Characteristics

The oscillation of the flame at a frequency lower than 200 Hz is low-frequency oscillation, that at above 1000 Hz is high-frequency oscillation, and that at 200–1000 Hz is medium-frequency oscillation. In the initial stage of combustion, the combustor pressure appears to have low-frequency oscillation at a frequency of 93.74 Hz. The flame also has low-frequency oscillation at a frequency of 92.77 Hz, which is very close to that of the combustor pressure, as plotted in Figure 14. In fact, flame oscillation is the direct cause of chamber pressure oscillation. In addition, the low-frequency oscillation of flame is closely related to the phase change of LOx. The dryness change of LOx during the combustion process is achieved by the temperature and pressure conditions in the LOx manifold. The FFT analysis of the dryness of LOx in the process was carried out, as shown in Figure 14.

It can be seen that the oscillation frequency difference between the chamber pressure and the LOx dryness is 5%, which is caused by the limited measuring point of LOx temperature. The LOx phase state is highly sensitive to temperature, and thus there is an error in the calculated LOx dryness, which is within an acceptable range. Therefore, the instability of the LOx phase state is the main factor that leads to the low-frequency oscillation of chamber pressure. Its impact is that the change of the LOx phase state leads to the change of LOx density, thus affecting the mass flow rate of LOx into the combustor, as described in Figure 8, which eventually leads to unstable combustion. When the liquid oxygen dryness is unstable, the chamber pressure will show low-frequency instability, and the oscillation frequency of liquid oxygen dryness and chamber pressure are almost the same. On the contrary, the low-frequency instability of chamber pressure will disappear.

#### 3.3.2. High-Frequency Flame Oscillation Characteristics

A high-frequency oscillation of the flame occurs during the whole combustion process of a LOx/methane swirl coaxial injector, which may lead to unstable combustion when it is coupled with the natural acoustic frequency of the combustor; therefore, it must be suppressed. Figure 15 shows the changes of high-frequency oscillation and intensity of flame and the spray frequency during the combustion process. The spray frequencies were obtained by controlling the similar momentum flux ratio (J) with the firing test. The trend and value of spray and flame oscillation frequency were almost the same, as plotted in Figure 15. It has been confirmed that the high-frequency oscillation of flame is caused by self-pulsation spray. The main factors affecting self-pulsation spray are the recess length and the gas–liquid ratio.

Kang summarized the formula of critical recess length (Lc) of the GLSC injector and determined the flow mode by normalized recess length (R), which is the ratio of actual recess length (Lc) to critical recess length (Lcr), as shown in eq 2:

\[
L_{cr} = \frac{D_{0,ex} - D_1}{2\tan(\alpha/2)}
\]

\[
R = \frac{L_c}{L_{cr}}
\]

where \(D_{0,ex}\) represents the outer diameter of the inner post, \(D_1\) represents the diameter of the exit of the inner post, and \(\alpha\) represents the spray cone angle of the GLSC injector. The spray cone angle of the GLSC injector in the recess chamber, which can be calculated by the momentum conservation method, is mainly related to the injector structural parameters and the LOx/methane injection pressure. When \(R\) is greater than 1, it indicates internal mixed flow; when \(R\) is equal to 1, it is critical mixed flow; and when \(R\) is less than 1, it means external mixed flow. When comparing the \(R\) value and the gas–liquid Reynolds number of the combustion process with the self-pulsation boundary of the GLSC injector summarized by Bai, the range of \(R\) values, in which self-pulsation will occur, is able to be determined, as depicted in Figure 16. The red curve represents the \(R\) value.
of the whole combustion process. It is found that the \( R \) value of the whole combustion process is in the range of the self-pulsation zone, as described in Figure 16. Therefore, it is proven that the high-frequency oscillation of flame is caused by the self-pulsation spray during the combustion process.

As indicated in Figure 15, the flame oscillation frequency increases gradually during engine operation. This is because the gas fraction of liquid-oxygen two-phase flow decreases, which leads to the rise of the flow rate of LOx mass entering into the combustor. However, the gas mass flow rate remains nearly stable (Figure 8), and thus the self-pulsation frequency increases,\(^2\) which results in the rise of flame oscillation frequency.

4. CONCLUSIONS

Experimental investigations were conducted to explore the working process of a LOx/methane engine, the flame spatial distribution, and the oscillation characteristics of LOx/
methane flame generated by a GLSC injector during the whole unsteady combustion process. Instantaneous flame images were obtained by the optical measurement with a high-speed camera. The research is concluded as follows:

The combustion process of a LOX/methane engine is mainly divided into the subprocesses of ignition, low-frequency oscillation combustion, quasi-steady state combustion, and shutdown. During the ignition subprocess, the flamelet is slender and tapered, and a recirculation zone forms near the injection panel. During the low-frequency oscillation combustion subprocess, the flame shape develops from cloak to cone, and the combustion zone gradually confines to the central recirculation zone. During the quasi-steady state combustion subprocess, the flame concentrates on the central axis of the combustor, and the intense combustion zone remains relatively stable. During the shutdown subprocess, the combustion zone gradually approaches the wall of the combustor and the injection panel, and a recirculation zone appears near the jet panel again, which gradually decreases and finally disappears. The shutdown subprocess has the longest duration, accounting for 39.7% of the whole combustion process. Therefore, it is necessary to pay attention to the thermal protection of the engine during this subprocess.

Within the course of the combustion process, the flame expansion angle increases greatly in both the low-frequency oscillation combustion subprocess and the shutdown subprocess, which is caused by the decrease in the gas−liquid momentum ratio. However, both the flame length and the normalized flame area increase initially and then reach the peak value in the quasi-steady state combustion subprocess.

At the initial stage of the LOX/methane combustion process, the instability of the LOX phase state leads to low-frequency combustion oscillation. In order to avoid low-frequency unstable combustion during engine operation, it is necessary to ensure that LOX is pure liquid. In addition, during the combustion process, the self-pulsation spray of LOX/methane will lead to the high-frequency oscillation of the flame for the GLSC injector. With the increase in the LOX manifold pressure, the LOX gradually changes from two-phase flow to pure liquid so that the mass flow rate of LOX entering the combustor increases. Meanwhile, the gas mass flow rate remains nearly constant, leading to the increased self-pulsation frequency of spray, which in turn elevates the high oscillation frequency of the flame.

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Notes
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