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Longitudinal combustion instability of a pintle injector for a liquid rocket engine combustor

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ABSTRACT

The longitudinal combustion instability characteristics of a pintle injector for a liquid rocket engine combustor are investigated experimentally. The effects of the propellant total momentum ratio (TMR) on the combustion oscillation characteristics and the characteristic exhaust velocity (C^*) efficiency are investigated. The time scales of the combustion oscillations are compared with various phenomena in the combustion chamber in order to identify dominating phenomena of each combustion oscillation mode. The target combustion pressure and the propellant mixture ratio are 0.5 MPa and 1.45, respectively. High-speed optical measurements for the CH^* chemiluminescence and backlit spray images are also conducted to investigate the oscillating combustion behaviors of the pintle injector. The amplitude of the pressure oscillation (P') increases with decreasing TMR. When the TMR is 0.73, the P'is approximately 50 % of the average combustion pressure, whereas the P' decreases to 20 % of the average combustion pressure when the TMR is increased to 2.35. Frequency characteristics of the combustion oscillations are affected by the TMR. When the TMR is smaller than unity, the pressure oscillations at the chamber acoustic natural frequencies are dominant, and the coupling between the heat release rate and the combustion chamber acoustics could occur. When the TMR is increased, low frequency oscillations whose frequencies are smaller than the fundamental natural frequency of the combustion chamber are observed. The time scale of the observed oscillation is close to the residence time of the combustion gas in the combustion chamber, and the convective process could cause the low frequency oscillations.

1. Introduction

The combustion instability or combustion oscillation has been one of the most challenging issues in the liquid rocket engine combustion. The oscillating combustion pressure increases vibration levels of a launch vehicle and deteriorate the payload environments. The combustion pressure oscillation also changes the heat transfer characteristics, and reduces the engine lifetime. The combustion instability sometimes leads a destruction of the engine and complete failure of the mission.

The combustion instability phenomena have been extensively studied during the development of new engines, and the knowledge can be found in the various literatures [1,2]. The mechanism of the combustion instability has not been fully understood, and the prediction of the combustion stability is still one of the most difficult tasks in the development of a new engine. Hence, the “cut-and-try” method, in which numerous number of the combustion test are conducted and passive suppression device such as acoustic resonators and/or baffle plates are added, is still adopted.

Combustion stability characteristics are affected by a lot of factors such as propellant injector configurations, propellant injection conditions, combustor geometries and existence of damping devices. Combustion stability characteristics of shear coaxial injectors, which are usually used in the cryogenic rocket engines, have been extensively carried out since the cryogenic propellant is widely used in a lot of launch vehicles currently operated. Optical measurements with high time resolutions are one of the most powerful tools to investigate unsteady combustion behaviors during combustion oscillations. Unstable combustion behaviors of shear coaxial injector for liquid hydrogen/liquid oxygen (LOX) rocket engine combustor has been studied, and the effect of the hydrogen injection temperature on combustion dynamics and flame behaviors have been investigated experimentally [3,4]. Combustion behaviors of the methane/liquid oxygen combustion under

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transverse oscillations forced by periodical blocking of the secondary nozzle were investigated, and the oscillating combustion behaviors were observed with the high-speed optical measurement [5,6]. The combustion behaviors under forced oscillating pressure with the similar experimental setup have been observed and corresponding numerical analysis have been also conducted [7].

The longitudinal combustion instability of shear coaxial injectors in a dump combustor have been investigated experimentally [8–12] and numerically [13–15]. Not only the instability phenomena of the injector themselves but also the approach for comparing the experimental and numerical results and the analytical techniques such as decomposition techniques have been carefully investigated [16,17].

The pintle injector is one of the promising candidate for a propellant injection system in a liquid rocket engine combustor due to the simple structure and throttling capability [18,19]. No combustion stability issues in the development of various pintle engines has been reported. It is believed that the pintle-type injector has preferable combustion stability characteristics. The simple structure and the combustion stability are driving factors to use the pintle injector in a new low cost engine due to the low manufacturing cost [20,21] and reduced risk of the combustion instability issue.

Even though the pintle injector is a flight proven technology, few fundamental studies on the pintle injector has been conducted, and the combustion dynamics of the pintle injector has not been clarified yet. A parametric study has been conducted and the effects of the injection parameters and combustor geometries on the combustion characteristics has been investigated [22]. Optical measurements for the combustion dynamics of a pintle injector has been conducted with a carefully designed two-dimensional combustor [23]. Unsteady spray combustion behaviors of the pintle injector has been visualized successfully [24,25]. As shown in the previous study, strong combustion instability can occur in the combustion chamber with a pintle injector, depending on the propellant injection parameters [26]. Since the combustion instability phenomena of the pintle injector have not been reported, the combustion instability characteristics of the pintle injector are not well known. Therefore, in this study, the effect of the propellant injection conditions on the combustion stability characteristics of a pintle injector and the detailed combustion oscillation behaviors are investigated experimentally. High-speed optical measurements of the oscillating combustion behaviors and the oscillating combustion pressure measurements are conducted simultaneously to investigate detailed combustion dynamics during combustion oscillations. As shown in the previous study [24], LOX injection velocity significantly affects combustion oscillation characteristics of the combustion chamber used in this study. Combustion experiments with different LOX injection velocities are conducted to investigate combustion oscillation modes of each experimental condition. Unsteady heat release characteristics are investigated with the optical measurement, and the oscillating combustion behaviors are discussed with the results of the high-speed pressure and optical measurements. The dynamic mode decomposition technique is used to extract the dynamic information of the oscillating combustion from the time-resolved optical measurement results.

2. Experimental setup

2.1. Combustion chamber

Figure 1 shows the structures of the experimental combustors used in this study. Figure 1(a) is non-optical configuration, and used for the experiments without optical measurements. The diameter and the length of the straight section is 100 mm and 455 mm, respectively. The chamber characteristic length (L^*) of the combustor is approximately 2.0 m. The static and dynamic pressures are measured at the combustor flange and the nozzle entrance, respectively. The combustion is initiated with a hydrogen/air torch igniter, which is located on the faceplate. No active cooling system is used, since the combustion duration is short. The throat diameter of the nozzle section is 49.8 mm and the expansion ratio is 2.25.

Table 1
Composition of the fuel (AP-7).

Name	Mass fraction [%]
Ethanol	85.5
1-Propanol	9.6
2-Propanol	4.9

Figure 1(b) shows the optical configuration. The first section of the combustor straight section is replaced with an optically accessible section. The other sections are identical to the non-optical configuration. A quartz cylinder whose inner diameter is 100 mm is inserted into the optically accessible section, and the combustion behaviors in the vicinity of the propellant injector can be visualized. Inert gas is supplied to the optically accessible section to protect the optical window.

The details of the optical section is shown in Fig. 2. The inner and outer diameter of the optical glass is 100 mm and 120 mm, respectively. The inert gas is supplied from the slit whose width is 0.1 mm on the faceplate. In this study, nitrogen gas is used as the purge gas. The optical accessibility of the optical section is shown in Fig. 2. The inner diameter of the combustion chamber is fully visualized. Since rectangular windows whose geometry 100 mm × 77 mm is made on the both sides of the housing for the optical glass, optical measurement with the backlit configuration can be conducted. Since the optical glass is a cylinder, the distortion of the image cannot be avoided as discussed in a previous study [16]. The rest of the optical section is made of stainless steel 304. The region from the faceplate to 15 mm downstream from the faceplate cannot be visualized due to geometrical restrictions.

2.2. Propellant injector

The fuel and oxidizer used in this study is AP-7 (Japan Alcohol Trading Co, Ltd.), which is a multicomponent alcohol, and liquid oxygen (LOX), respectively. The composition of the AP-7 is shown in Table 1.

The details of the injector are shown in Fig. 3. LOX is injected radially through the gap between the pintle cap and the body. This configuration is called oxidizer-centered configuration. Three types of the pintle caps are used to change the injection area and to control the injection velocity of the LOX. The diameter of the pintle cap is 20 mm, and the cap is supported by a supporting bolt. LOX is supplied to the LOX injection gap through a supporting structure with 12 holes whose diameter is 2 mm located in the LOX manifold. It should be noted that there is a pressure loss at the supporting structure. The fuel is injected through the gap between the fuel control ring and the body, and the gap distance is 0.2 mm. The skip distance, which is the length from the fuel injection gap to the impingement point, is 15 mm. Gas-pressurized feed system is used to supply propellant to the combustion chamber. Helium gas is used for the pressurization of the propellant, and the penetration of the pressurizing gas into the propellant (especially LOX) can be neglected since the liquefying temperature of helium is much lower than that of LOX.

3. Measurement and analysis

3.1. Pressure, temperature and flow rate measurements

Pressures at propellant feedlines and the test articles are measured with strain gauge type pressure transducers (Kyowa: