# 博士論文（要約）

A Study on Combustion of Pintle-type Injector for

Ethanol/Liquid Oxygen Rocket Engine

（エタノール/液体酸素ロケットエンジンにおける

ピントル型噴射器の燃焼に関する研究）

榊　和樹

The propellant injection system for liquid rocket engine combustors has significant effects on the combustion characteristics of the rocket engine combustor. Various propellant injection systems have been developed in order to achieve the high propulsion performance and the stable combustion.

The pintle-type injector is one of the propellant injection systems for rocket engine combustors. Since the structure of the pintle-type injector is simple, the pintle-type injector has been used for propellant injectors for low cost rocket engines. Thrust control capability of the pintle-type injector is one of the most important features of the injector. The pintle-type injector is used for a propellant injector in the Lunar Module Descent Engine (LMDE), which is required to operate under various operating conditions, and the LMDE successfully operated in various missions due to the thrust control capability of the pintle-type injector.

The pintle-type injectors have been used in the various rocket engines, and the developments of the rocket engines with pintle-type injectors have been conducted based on the empirical knowledges. The developments have been conducted with try-and-error styles, and few systematic studies on the combustion characteristics of the pintle injector have been carried out.

Therefore, an experimental study on the combustion of the pintle-type injector is conducted in order to clarify fundamental combustion characteristics of the pintle-type injector. Axisymmetric and rectangular combustors are used in this study. The axisymmetric combustor is used to investigate the effects of the propellant injection conditions on the combustion characteristics such as combustion efficiency and the combustion stability. The rectangular combustor is used for optical measurements for the combustion behaviors of the pintle-type injector. The high-speed optical measurements are also conducted with the axisymmetric combustor in order to investigate the combustion behaviors under combustion oscillation conditions. The CH* chemiluminescence and the backlit spray images are observed with two high-speed cameras.

In the experiments with the axisymmetric combustor, the effects of the combustion chamber length on the characteristic exhaust velocity (C*) are investigated. The combustion pressure is approximately 0.45 MPa, and the O/F is varied from 1.0 to 2.2. When the combustion chamber length is increased from 320 mm to 455 mm, the C* efficiency increases by approximately 5 %. This could be because the residence time of the combustion gas in the combustion chamber is increased when the combustion chamber length is increased, and the amount of the vaporized propellant could increase.

In the next test campaign, the effects of the propellant total momentum ratio (TMR) on the C* efficiency and the combustion stability characteristics are investigated. The TMR is controlled by changing the LOX injection velocity, whereas the O/F is kept constant at 1.45.

The combustion pressure is approximately 0.45 MPa, though the combustion pressure slightly changes due to the change in the C* efficiency. The C* efficiency decreases from 94 % to 82 % when the TMR is increased from 1.1 to 2.3. This could be due to the mixing characteristics in the vicinity of the propellant injector. The unity TMR is the most appropriate conditions for the two impinging propellant jets in terms of the mixing.

The combustion stability is also related to the change in the C* efficiency. A positive correlation between the amplitude of the combustion pressure oscillation and the C* efficiency is observed. The amplitude of the combustion pressure oscillation is more than 20 % of the average combustion pressure, and the non-linear effects could affect the average combustion pressure, which is known as average pressure shift or DC shift. It is well known that the average combustion pressure increases when strong longitudinal combustion oscillations occur in solid rocket motors due to a non-linear effect. In this study, the average combustion pressure increases with the increase in the amplitude of the combustion pressure oscillation, whereas the propellant mass flow rates are constant. Therefore, the C* efficiency increases with increasing amplitude of the combustion pressure oscillation

When the TMR is 0.75 or 1.1, the amplitude of the combustion pressure oscillation is approximately 50 % of the average combustion pressure. In these cases, the oscillation at the frequency of the first longitudinal mode of the combustion chamber is dominant, even though the oscillations at harmonic frequencies are also observed. The combustion oscillation in these cases could be caused by the coupling between the combustion chamber acoustic mode and the heat release due to the combustion reaction. When the TMR is increased to 2.3, the oscillations at 400 Hz and 800 Hz are observed, whereas the oscillations at the combustion chamber acoustic modes are weak. Since the time scale of the 400 Hz oscillation corresponds to the combustion chamber residence time, the combustion oscillation could be a convective mode oscillation such as the entropy mode.

The combustion experiments with the rectangular combustor, which is designed for the optical measurements for the combustion behaviors of a pintle injector in the cross section of the axisymmetric combustor, are conducted. The CH* chemiluminescence and the backlit spray images are observed with high-speed observation systems in order to investigate the effects of various injection parameters on the spray and flame structures of the pintle injector.

The combustion experiments with both the fuel- and oxidizer-centered configurations are conducted in order to investigate the effects of the injector configurations of the pintle injector on the combustion characteristics and combustion behaviors. The O/F is varied from 1.0 to 2.2 whereas the combustion pressure is kept constant at 0.37 MPa. The C* efficiency in the fuel-centered configuration increases with the increase in the TMR, whereas the opposite tendency is observed in the oxidizer-centered configuration. This could be explained by the difference in the spray structures. When the TMR is increased in the fuel-centered configuration, the spray penetration angle, which is defined as the angle between combustion chamber lower wall and the direction along which most of the propellant droplets scatter, decreases, and the amount of the propellant impinging on the combustor upper wall decreases. On the other hand, the spray penetration angle increases with increasing O/F in the oxidizer-centered configuration, and the amount of the propellant droplet impinging on the combustor upper wall also increases. The impingement of the propellant on the combustor upper wall could deteriorate the combustion efficiency since some of the propellant works as the coolant of the film cooling and does not contribute the heat release in the combustion chamber.

The combustion experiments with the different TMR are conducted in order to evaluate the effects of the TMR on the combustion characteristics and the combustion behaviors in both injection configurations. In the oxidizer-centered configuration, the C* efficiency is maximum when the TMR=1.0, whereas the C* efficiency in the fuel-centered configuration increases with a decrease in the TMR. The CH* chemiluminescence distributions in the case with TMR=3.6 is different from the others. When the TMR is large, heat release distribution could be different due to the impingement of the propellant droplet on the combustor wall.

Unsteadiness of CH* chemiluminescence in various injection conditions were evaluated using descriptive statistics distributions. The standard deviation at the impinging point of the two propellant jets is large, hence, heat release fluctuations in the region could be large, whereas the coefficient of variation is large in the vicinity of the combustor faceplate and the upper wall. Therefore, when the absolute value of the heat release is discussed, the phenomena in the vicinity of the impinging point should be considered.

The combustion stability characteristics of the pintle injector in the axisymmetric combustion chamber are investigated with high-speed imaging techniques. Simultaneous measurements for CH* chemiluminescence and backlit spray images are conducted to investigate the unsteady combustion behaviors under oscillating combustion conditions. The observed flame images are analyzed with decomposition techniques such as Proper Orthogonal Decomposition and Dynamic Mode Decomposition techniques in order to extract low order flow field characteristics.

The combustion pressure and the propellant mixture ratio are 0.45 MPa and 1.6, respectively. The TMR is controlled by changing the LOX injection velocity, and the LOX injection velocities are changed by changing the LOX injection area, whereas the propellant mass flow rates are kept constant. Two different combustion oscillation modes are observed when the TMR is changed.

When the TMR is 0.76, the amplitude of the pressure oscillation is 52 % of the average combustion pressure. Strong peaks were found at the longitudinal natural frequencies of the combustion chamber, and the oscillation with the first longitudinal natural frequency was dominant. The CH* chemiluminescence intensity oscillate with the first longitudinal natural frequency. The dominant oscillating behaviors were captured with the both POD and DMD techniques. In the dominant POD mode, not only the fundamental but also the harmonic frequency components were included, though the fundamental frequency mode is dominant. The first and second longitudinal natural frequency modes were detected in the DMD analysis. Therefore, the combustion oscillation in this case was caused by the coupling between the oscillating heat release and the combustor acoustics. The descriptive statistics distribution of the CH* chemiluminescence intensity indicated that the local ignition and quenching could be caused by the acoustic wave.

When the TMR is increased to 2.48, the combustion oscillation characteristics were changed. The amplitude of the combustion pressure oscillation is 18 % of the average combustion pressure. The high frequency components in this case are much weaker than in the case in which TMR = 0.76. Even though the amplitude of the combustion pressure oscillation is weak, several peaks were observed in the low frequency region of the power spectral density for the combustion pressure. The oscillations with 400 Hz and 800 Hz were dominant in this case. These oscillations could be related to the convective mode. Two distinct reaction zones with the different oscillation frequencies were observed. These two zones is divided by the propellant spray. The heat release oscillation in the upstream and the downstream of the propellant spray oscillate at 400 Hz and 800 Hz, respectively. These two modes were captured by the DMD analysis.