Flame Visualization of GOX/GCH4 Pintle Model Combustor

Dae Hwan Kim[1], Hyeontaek Jo[2], Subeom Heo[1], Jaehong Choi[1], Inho Kim[1], Youngbin Yoon[3]
[1] Department of Aerospace Engineering, Seoul National University
Seoul, Republic of Korea
[2] Department of Mechanical and Aerospace Engineering, Seoul National University
Seoul, Republic of Korea
[3] Institute of Advanced Aerospace Technology, Seoul National University
Seoul, Republic of Korea

Abstract

Pintle injector is a bipropellant coaxial injector in which two propellants are injected radially and axially, then collide with each other for atomization. Due to its strength including combustion stability, throttling capability, and its simplicity, the pintle injector is gradually accepted for reusable launch vehicle throttling engines and studied for its spray and combustion characteristics. Though the combustion stability of the pintle injector is known as one of the main advantages, its detailed combustion characteristics are not investigated in depth, especially the dynamic characteristics. In this research, an oxidizer-centered GOX/GCH4 pintle model combustor is designed for atmospheric gas-gas combustion test, with proper wall confinement condition. The flame shape is analyzed based on the OH* chemiluminescence and OH-PLIF visualization. The reaction surface of the pintle injector is truncated cone-shaped and experiences a great fluctuation under high-radial flow momentum conditions. The stability of the flame is judged based on the chemiluminescence images and the dynamic pressure measurement. The injector transfer function and flame transfer function are measured by applying acoustic excitation on each propellant line with the speaker.

1 Introduction

The demand for launch vehicle is growing due to expansion of the satellite market [1]. The 5th generation communication technology, satellite internet, global positioning system, and satellite imaging services are all in need of launch services [2]. As the demands grow, lowering the launch cost became critical to survive in the launch vehicle market and several reusable launch vehicles are under development now. The vertical landing method is a dominant method in fully reusing the launch vehicle by retrieving, which is impossible without throttleable main engine. The pintle injector is known to be appropriate for deep throttling with high combustion stability, and had been used for throttleable engines since LMDE

Correspondence to: ybyoon@snu.ac.kr

(Lunar Module Descent Engine) [3]. Several groups have studied about the spray and combustion characteristics of the pintle injector [4-10], but few have concentrated on its dynamic combustion characteristics.

Lee et al. studied the correlation between spraying conditions – annular gap distance, skip distance and mass flow rate, and spray characteristics – spray angle and droplet size, of the pintle injector [4-6]. Kim et al. [7] and Heo et al. [8] introduced a new geometrical design in pintle tip and analyzed its effects on spray characteristics. Son et al. studied on the spray characteristics of the canted pintle tip with both experimental and numerical methods [9-10]. The researches about the spray characteristics of the pintle injector all points out that total momentum ratio (TMR), defined as (1), of two fluids is the dominant factor in determining the spray angle. The momentum of radial (r) and axial (a) flow is represented as product of the mass flow rate ($\dot{m}$) and exit velocity (u).

$$TMR \equiv \frac{\dot{m}_r u_r}{\dot{m}_a u_a} \qquad (1)$$

Jin et al. have experimentally studied about the gas-liquid pintle injector, especially concentrated on the atomization process [11]. From the simplified experiment, it was concluded that the atomization of the pintle injector is mainly due to the Kelvin-Helmholtz instability.

Sakaki et al. studied the combustion characteristics of the LOX/mixed ethanol pintle combustor [12]. The characteristic velocity efficiency and the combustion pressure oscillation amplitude had negative correlation with TMR. The combustion oscillation behavior itself also varied by TMR – thermo acoustic mode dominated at low TMR condition, while entropy convective mode dominated at high TMR condition. Yue et al. [13] and Jin et al. [14] have investigated the combustion characteristics of the pintle combustor with numerical methods. The evaporation rate of the propellant mainly controlled the combustion process, and the LOX particle diameter after atomization had negative correlation with the combustion efficiency and combustion stability. Liberatori et al. have also pointed out through numerical analysis that as the LOX particle diameter increases the core recirculation zone is strengthened [15]. Son et al. investigated the flame shape of the gas-gas pintle atmospheric combustor [16]. The flame shape was classified into two types, shear layer flame and tip-attached flame, mainly determined by the radial momentum flow. Boettcher et al. have investigated the gas flow of the gas-gas pintle injector under pressurized condition, concentrating on the shock and vortex structure around the pintle post and tip [17].

Despite the wide study on the pintle injector, its fundamental dynamic combustion characteristics were not dealt in depth. Furthermore, most research did not include the wall confined condition, despite its importance in the pintle injector – due to single injector usage in a combustor. In this research, the fundamental static and dynamic combustion characteristics of GOX/GCH4 pintle model atmospheric combustor with wall confined condition are studied for wide O/F ratio range. The basic combustion characteristics including flame angle, flame shape, stability map, injector transfer function (ITF) and flame transfer function (FTF) are covered in this paper.

2 Experimental Apparatus and Methods

The pintle model combustor used in this research is designed based on the 400 N LOX/GCH4 pintle engine. The model combustor is designed to study the fundamental flame characteristics and investigate its stability under atmospheric condition. As only single pintle injector is used in the combustor, unlike other type of injectors, the flame angle of the single injector is the main variable for flame characteristics. Since, the flame angle is mainly controlled by the total momentum ratio (TMR), the model combustor is designed to have identical TMR with the real engine for analogy. The cross-section of the model combustor is selected as a square for flame visualization. The cross-section of the pintle combustor and its specification is given as Fig. 1 and Table 1. The quartz window for flame visualization is film cooled with gas nitrogen. The combustor exit is blocked with movable plug nozzle to change the combustor length, except when measuring the FTF in which open end condition is needed.

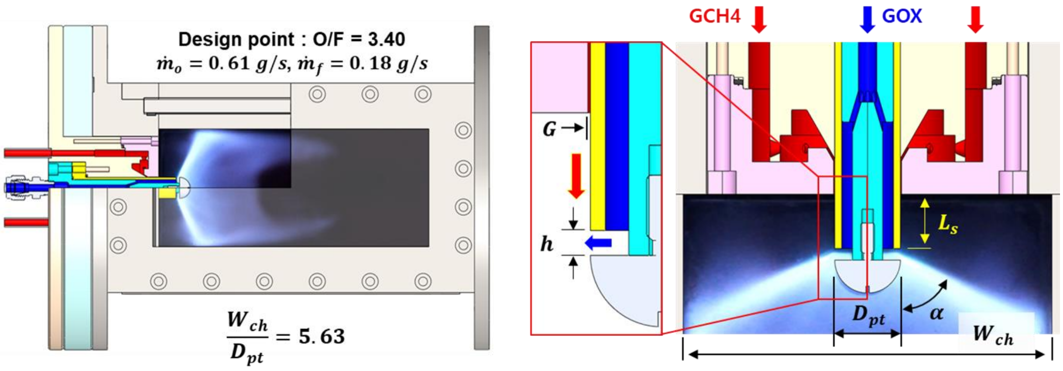

Figure 1: Schematic of the atmospheric pintle model combustor (left) and the close-up cross-section of the pintle tip (right).

Table 1: Specification of atmospheric pintle model combustor.

Parameter [Unit]		Value
Pintle Tip Diameter [mm]		11
Combustor Cross-Section [mm x mm]		80 x 80
Annular Gap (G) [mm]		0.5
Pintle Height (h) [mm]		0.1 ~ 0.4
Canted Angle [deg]	Pintle Tip (α_1)	15
	Pintle Post (α_2)	25
Mixture Ratio (O/F)		2 ~ 10
Propellant Volume flow rate (O/F = 3.4) [slpm]	Oxygen	41.03
	Methane	24.05
Combustor Length [mm]		1100 ~ 1900

The gaseous oxygen and methane were supplied through mass flow controllers (LineTech, M3300V, uncertainty = ±1%) at 290±5 K. The mixture ratio was varied with fixed overall volume flow rate of supply gas. The gaseous methane was supplied approximately 1 s after gaseous oxygen, while the pilot flame of hydrogen-gas torch ignitor is on.

The FTF was measured by generating sine wave excitation of 100 – 1500 Hz range frequency in both gas supply line with speaker (SU-150EF, Sammi Sound Tech Co. Ltd.). The speaker input voltage was controlled to maintain uniform excitation strength of each supply gas to 5%. The excitation strength is the ratio of velocity perturbation of the gas flow and its average value, defined as (2). The gas flow velocity is measured through hot wire anemometer (MiniCTA 54T42, Dantec Dynamics) installed in the gas supply line.

$$\text{Excitation Strength} \equiv \frac{u'}{\bar{u}} = \frac{u - \bar{u}}{\bar{u}} \tag{2}$$

The light intensity of the flame, measured with a photomultiplier tube (PMT) (H7732-10, Hamamatsu) installed with 320±20 nm bandpass filter, is considered to be proportional to the heat release of the combustion at the moment. The FTF was measured under open boundary conditions for nearly constant velocity fluctuation for each modulation frequency, so that the photo-electric intensity from the PMT is directly proportional to FTF gain. The FTF was measured for O/F ratio of 2.0 – 10.0.

The pintle combustor flame is visualized by OH* chemilu-minescence with 100 mm x 80 mm field of view. The image was acquired with CMOS (complementary metal-oxide-semiconductor) camera (HighSpeed Star 8, LaVision) at 5 kHz, using a UV-enhanced lens (100 mm, f/2.8, LaVision) and a 310 nm bandpass filter (1108760VZ, LaVision). The chemilu-minescence image was used to analyze the flame shape.

3 Results and Discussion

The flame could be categorized into three types based on the fluctuation index K, which is defined as (3). The majority of the cases show Type B flame, which has wrinkled reaction surface due to the K-H instability. Type A flame has steady reaction surface, while Type C flame is greatly unstable with radial perturbation.

$$\text{Fluctuation Index} : K \equiv \frac{\sum c_v\,(x,\ y)}{\sum \mu\,(x,\ y)} \tag{3}$$

$$\left(\begin{array}{rl} \text{where,} \quad c_v(x,y) = & \text{coefficient of variation of } i(x,y), \\ \mu\,(x,\ y) = & \text{average of } i(x,y) \\ i(x,y) = & \text{the pixel's OH radical chemiluminescence intensity} \end{array} \right)$$

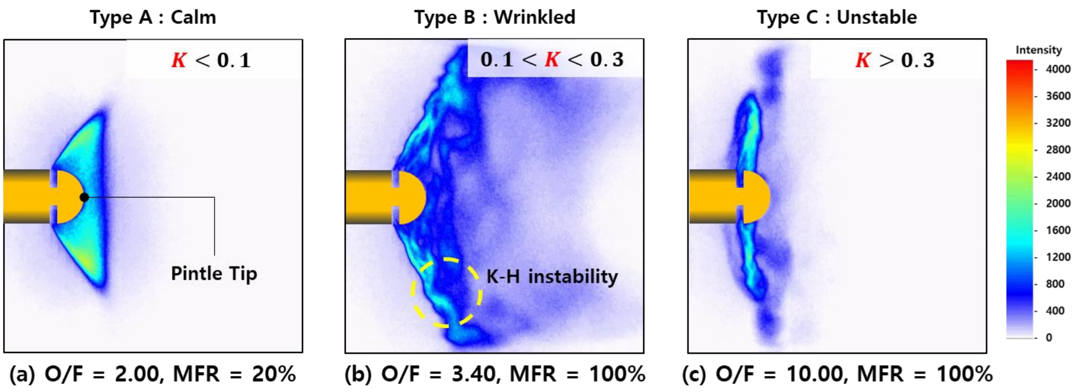

Figure 2: Three types of the pintle injector flame observed in the research.

Type C flame fluctuated radially, and was observed under condition of high radial flow momentum and high TMR. The overall stability map by radial flow momentum and TMR is depicted in Fig. 3. The color and size of the bubbles represents the fluctuation index K. The flame became unstable with high radial fluctuation under small gaseous oxygen injection area, high mass flow rate, and high mixture ratio condition which all leads to high radial momentum.

The rest of the results including the OH-PLIF of the flame, ITF, and FTF are work in process and will be presented in the conference poster session.

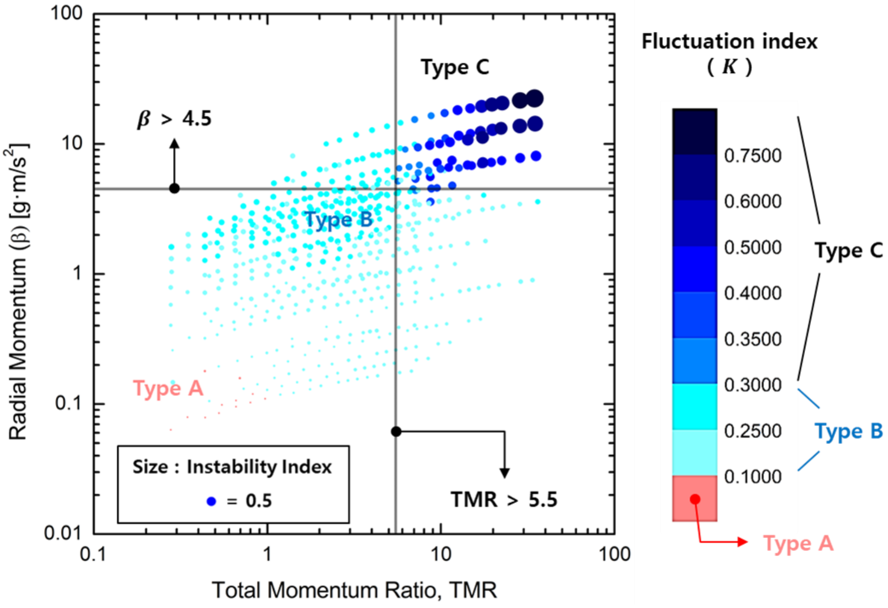

Figure 3: Stability map of the pintle injector flame by radial momentum and TMR.

Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea Government (MSIT) Space Challenge Project (2021M1A3B8075809) contracted through the SNU Future Innovation Institute; and by the NRF grant funded by the Korea Government (MSIT) (2021R1A2C2003759). Furthermore, the first and third author of this work were financially supported by the Seoul National University as beneficiaries of the Fellowship for Fundamental Academic Fields and the Fellowship by SNU Innovation Program respectively.

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