Experimental Study on the Performance of Rotating Detonation Engine with Aerospike Nozzle

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1 Introduction

In Rotating Detonation Engine (RDE), Pressure-gain Combustion (PGC) based on the Humphrey cycle is performed. The thermodynamic efficiency of Detonation Combustion is higher than Deflagration Combustion, which is based on the Brayton cycle. Furthermore, RDE has a smaller combustion channel than pressure-constant combustion engines. It is because RDE has a great thrust-to-weight ratio. Due to these advantages, Various studies on RDE have been conducted in recent years. Rankin et al. [1] have studied specific thrust and specific impulse according to the equivalence ratio and mass flow rate of gaseous hydrogen-air propellants. Han et al. [2] have studied the tendency of thrust and specific impulse when with or without a conical nozzle. Fan et al. [3] have studied the detonation velocity for wavenumber and the comparison of the wavenumber of gaseous hydrogen-gaseous oxygen detonation and gaseous methane-gaseous oxygen detonation. In this paper, the specific impulse and detonation velocity of RDE are experimentally studied for various contraction ratio conditions in which the aerospike nozzle is engaged or not engaged.

2 Experiment

The experimental study was carried out at Inha Jet Propulsion Laboratory in Korea. To conduct the experimental study, the RDE model and Aerospike nozzle were made as shown in Fig 1. The outer/Inner body diameter is 58/50 mm and the combustion channel length is 62.5 mm. Fuel/Oxidizer injectors are impinging injectors and consist of 72 holes with a diameter of 1 mm. Fuel and Oxidizer are injected from each plenum into the combustion channel through injectors. The gaseous hydrogen-gaseous oxygen Pre-detonator starts the RDE model. The Aerospike nozzle has a conical shape with a half angle of 15°. Considering the connection with the RDE model, the Aerospike nozzle has a thread behind it. Also, centerbodies are made for changing the nozzle throat area. The nozzle throat of the centerbodies has the same inclination angle as the aerospike nozzle. Each contraction ratio (ε) is 1, 1.56, 2.55. Contraction ratio $\varepsilon = A_{throat}/A_{channel}$. Several types of measuring equipment are being used to measure the results of the experiment. Fuel/Oxidizer plenum pressure and Combustion channel pressure are measured by Static pressure sensors. Mass flow rates are measured by a mass flow meter and equivalence ratios are calculated by measured mass flow rate results. 500 N Loadcell was used to measure RDE's thrust. Initially, the Loadcell Calibration test was conducted, and then the factor per weight was calculated.

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After calculation, we used that factor in the experiment. Detonation wave velocity was observed through High-speed Camera (Phantom v2511) results and calculated through the Fast-Fourier Transform (FFT) of Ion probe measurement results. The measurements of pressure, mass flow rate, thrust, and ion probe results are collected by the data acquisition system.

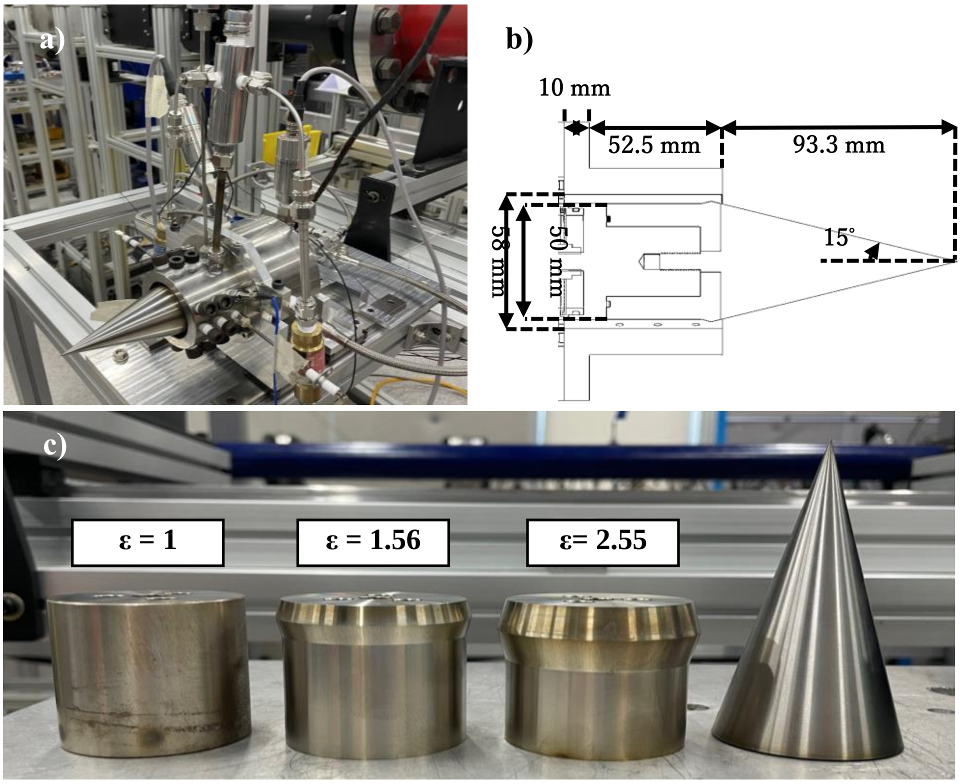

Figure 1: a) RDE Model with Aerospike Nozzle, b) Scheme of RDE Model, c) Centerbodies for various contraction ratios and Aerospike nozzle

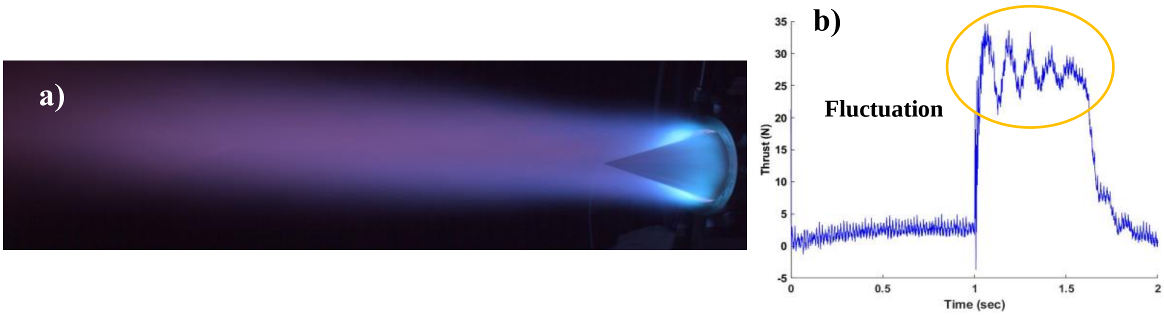

Figure 2. a) Picture of RDE operation, b) Typical thrust measurement results outline

In this experiment, we used gaseous methane-gaseous oxygen propellants in all conditions. We aimed to observe and analyze the specific impulse and detonation velocity for various contraction ratios in this experiment. Experimental conditions are to change the nozzle throat area in addition to the condition with the aerospike nozzle (Nozzle) and without the aerospike nozzle (Bluff). The total mass flow rate condition was 30 ± 1.0 g/s and the equivalence ratio range was 1.3 to 2.0. Choking at the nozzle throat occurred in all cases except for the condition of ε=1.

Figure 2. shows a picture of the RDE operation and a typical result outline of thrust measured by the loadcell. As shown in the graph, the start of the RDE operation is from 1 sec and the operation time is 0.5 sec. Thrust data results in fluctuation during operation time. This is caused by a strong explosion

after initiation. Therefore, we average the thrust data over the operating time and consider the averaged data as thrust data. At last, the specific impulse (I_{sp}) was obtained using averaged thrust data. Specific impulse $I_{sp} = F_{thrust}/(\dot{m} \cdot g)$.

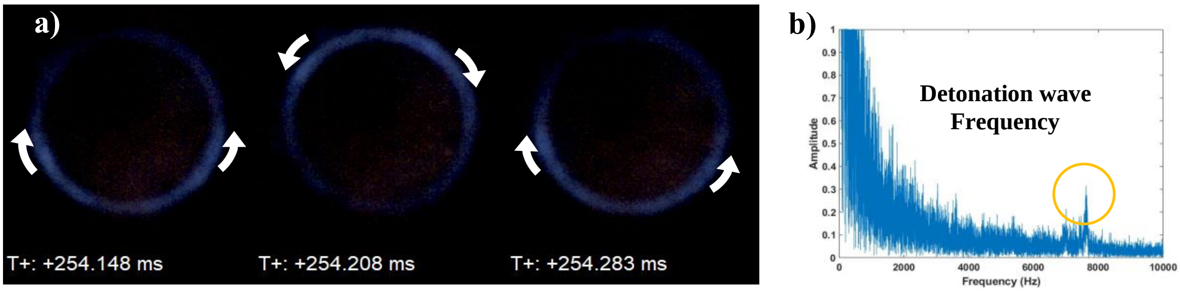

Figure 3. a) snapshot of propagating detonation wave capture at 256 × 256 resolution and 200,000 fps, b) FFT calculation results of ion probe measurement results

Figure 3. shows snapshots of propagating detonation wave captured at 256 × 256 resolution and 200,000 fps and FFT calculation results of ion probe measurement results. Wavenumber and direction of detonation wave are derived from snapshots. Based on the direction of detonation wave emitted form the Pre-detonator, the same direction is defined as 'Co-' and the other direction is defined as 'Counter-'. In this case, detonation velocity through visualization results is 1357.17 m/s and through FFT calculation of ion probe results is 1350.21 m/s. The wavenumber in this case is 1 Co-/1 Counter-. In the case of ε = 2.55, we can't obtain detonation velocity and wavenumber in snapshots because the size of the nozzle throat is too small to obtain visualization results.

3 Summary

In this present study, we observed the specific impulse and detonation velocity of RDE with or without an aerospike nozzle under various contraction ratio conditions. Table 1 and Table 2 are the experimental results of all contraction ratio conditions with or without an aerospike nozzle. Overall, specific impulse under nozzle conditions is much larger. As shown in Table 1, the specific impulse result was increased in the cases where the equivalence ratio was close to 1.5, and where the contraction ratio was large. On the contrary, as shown in Table 2, the specific impulse result was increased in the case where the equivalence ratio is higher. The detonation velocity result was increased in cases where the equivalence ratio was close to 1.5. However, there was no significant change in detonation velocity depending on the contraction ratio or bluff/nozzle conditions.

4 Acknowledgement

This work was supported by the National Research Foundation of Korea funded by the Ministry of Science and ICT under Grant. (2022M1A3C2076724, Future space education center)

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Table 1: Comparison of Thrust and Detonation Velocity under various contraction ratio conditions (Nozzle Condition, Total mass flow rate = 30 ± 1.0 g/s)

Case	Equivalence Ratio	Specific Impulse (s)	Detonation Velocity (m/s)	Wavenumber
ε = 2.55	1.57	146.17	1306.27	-
	1.89	108.54	1294.23	-
ε = 1.56	1.68	94.05	1321.03	1 Co-
	1.95	88.49	1294.74	2 Co- / 2 Counter-
ε = 1	1.37	62.62	1362.43	1 Counter-
	1.75	55.75	1350.21	1 Co- / 1 Counter-

Table 2: Comparison of Thrust and Detonation Velocity under various contraction ratio conditions (Bluff Condition, Total mass flow rate = 30 ± 1.0 g/s)

Case	Equivalence Ratio	Specific Impulse (s)	Detonation Velocity (m/s)	Wavenumber
ε = 2.55	1.58	93.78	1318.32	-
	1.9	99.74	1311.19	-
ε = 1.56	1.68	73.67	1362.26	2 Co- / 2 Counter-
	1.93	83.10	1307.97	2 Co- / 2 Counter-
ε = 1	1.65	50.26	1352.08	1 Counter-
	1.82	52.87	1379.22	1 Co- / 1 Counter-