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Experimental Study on the Propagation Characteristics of Rotating Detonation Engine by JISC Fuel injector configuration

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Abstract

In this study, the operation characteristics of the rotating detonation engine (RDE) are confirmed by the shape of the fuel injector that affects the RDE performance. The experiment utilizes a slit-type fuel injector with a 2-dimensional effect and a hole-type fuel injector with a 3-dimensional effect originating from side vortex such as counter-rotating vortex pairs. It is similar to the fuel injection structure of RDE and the transverse jet in supersonic crossflow (JISC). The tendency of the jet penetration affecting the fuel performance was confirmed and quantified. The jet moment ratio of gaseous ethylene injected perpendicularly to the flow of gaseous oxygen was calculated, and the jet penetration height was obtained by using the empirical correlation. The relationship between gaseous ethylene and gaseous oxygen stagnation pressure was derived according to the calculated jet penetration height and RDE channel width. The detonation rate was confirmed by fast Fourier transform (FFT) analysis, and the hole-type fuel injector showed a 10% higher value than the slit-type fuel injector. In addition, when the hole-type experimental results were compared, it was inferred that there was a correlation between the jet moment ratio and the fuel mixing performance.

Keywords: *Rotating Detonation Engine (RDE), JISC Fuel Injector, Detonation Velocity*

1. Introduction

Recently, as the efficiency improvement of the propulsion engine reaches its limit, detonation, which has the possibility of pressure gain combustion, propulsion systems have been researched actively. The detonation engine with the Humphrey having high efficiency compared to the Brayton cycle has been actively studied during the last decades [1-3]. Earlier, studies aimed at capturing the phenomenon of detonation within the chamber, such as PDE, were actively pursued [4,5]. However, when considering the similarity to gas turbines and the continuous operational characteristics, rotating detonation engine (RDE) was recognized to offer numerous advantages compared to pulse detonation engine (PDE) [6,7]. Detonation propagation characteristics in a rotating detonation engine (RDE) are affected by geometry, propellant mixture, etc [8-12]. In particular, the propellant mixture is a factor determined by the injector. Research on injectors should be carried out, including for this reason, and studies are being conducted [13]. Kindracki et al. compared the detonation speed calculated by the peak pressure value obtained from the annular rotating detonation engine experiment, and the performance was compared according to the shape [14]. Goto et al. measured the detonation wave velocity, which rotates along the annular RDE, was measured with the position and number of hole-type injectors as variables [15]. This study aims to investigate the operating characteristics of the RDE by considering the fuel injector geometry as a variable that influences RDE performance. The injection performance of the hole-type injector will be calculated using empirical equations, and the mixing performance between the hole-type and slit-type injectors will be examined based on the detonation velocity.

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2. Experimental apparatus

The schematic of the annular type RDE used in this experiment is shown in Fig. 1. The experimental RDE device can be configured not only in a circular shape but also in various chamber configurations [16,17]. The fuel consists of gaseous oxygen and gaseous ethylene, which are injected into the channel from a 0.46 mm slit for oxygen and either a 0.3 mm slit or a set of 47 holes with a total area of 1 mm² for ethylene. The width of the channel, which affects the maintenance of the detonation wave due to its correlation with the detonation cell width, is 4.5 mm, and the inner diameter is 50 mm. The length of the channel is 75 mm, and the expansion angle of the conical body to be applied later is 30°. Initiation of RDE was performed using a pre-detonator based on the same as the pulsed detonation engine. The internal diameter of the PDE is 4.22 mm, and its length is 150 mm. This PDE configuration was designed with reference to previous studies, and the diameter of the PDE is equal to the inner diameter of a commercial 1/4-inch pipe tube [18]. PDE, as a result of prior research efforts, had gradually succeeded in the development of small-scale PDEs from large-scale ones [19-23]. To achieve stable detonation wave generation inside the RDE channel, the pre-detonator was installed tangentially to the channel. In this study, PCB's ICP type high-speed dynamic pressure sensors and high-speed camera were used to investigate the characteristics of the rotating detonation engine. For the analysis of propagation characteristics, fast Fourier transform (FFT) and short time Fourier transform (STFT) were conducted using the results from the ICP type dynamic pressure sensor. The high-speed camera was installed at the rear of the RDE exhaust direction and captured the inside of the annular RDE chamber.

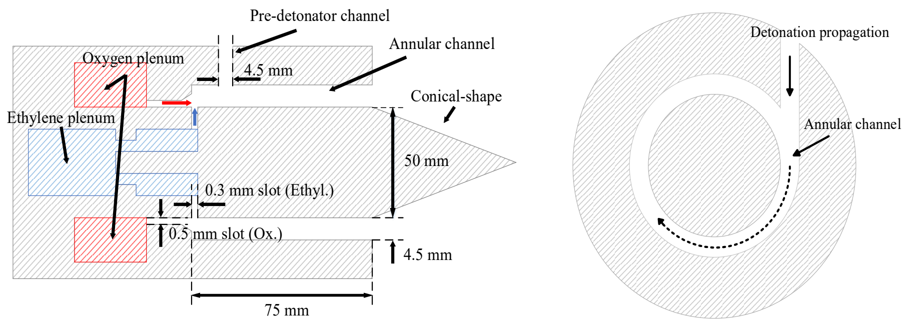

Fig 1. Schematic of RDE experiment model [24]

To confirm and quantify the performance trend of the hole-type fuel injector's spray characteristics, an empirical correlation was utilized to determine the jet penetration height. The jet penetration height based on the momentum ratio was calculated using equation (1) derived from the research findings of Gruber et al [25]. Fig. 2 presents the results of the calculated penetration distance based on the jet momentum ratio. Due to the similar structure to a scramjet, the oxidizer flow becomes the freestream value, while the fuel flow becomes the jet value. Therefore, the jet momentum ratio can be calculated by substituting the fuel's properties into the jet values and the oxidizer's properties into the freestream values.

$$\frac{y}{d_j J} = 1.23\left(\frac{x}{d_j J}\right)^{1/3} \quad (1)$$

$$P_{0,GO_2} = 0.7396 P_{0,GC_2H_4} - 5.833 \times 10^{-4} \quad (2)$$

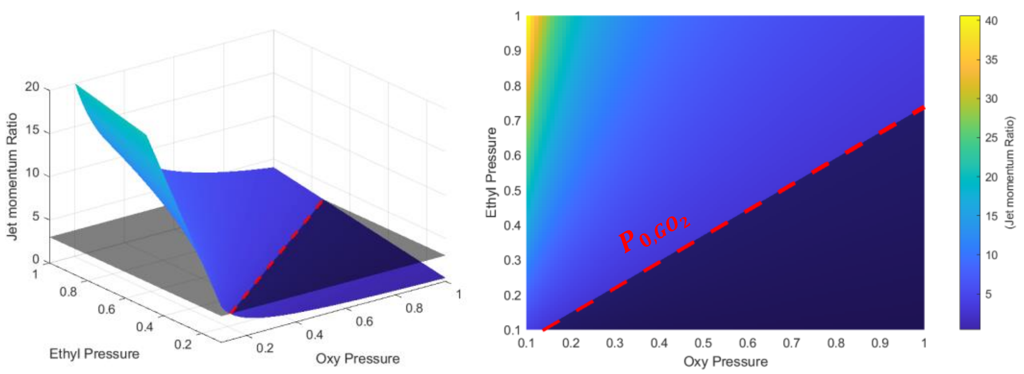

Fig 2. Jet momentum ratio relationship between oxidizer and fuel injection pressure

The sizes of the fuel injectors used in the experiment are listed in Table 1. The fuel injection structure and the unwrapped schematic are depicted in Fig. 3. The slit-type fuel injector has a spacing of 0.3 mm and uniformly injects fuel in the circumferential direction. The area of the slit is about 47.0 mm^2. The hole-type fuel injector has a square shape, and 47 holes with a 1 mm^2 area are evenly distributed at a spacing of 5.68 mm. The total area of the holes is approximately 47 mm^2, which is the same as the slit-type injector. Fuel is injected at the end of the expansion area of the oxygen injector. Oxygen was injected through the 0.46 mm slot in both cases, and it was injected parallel to the channel.

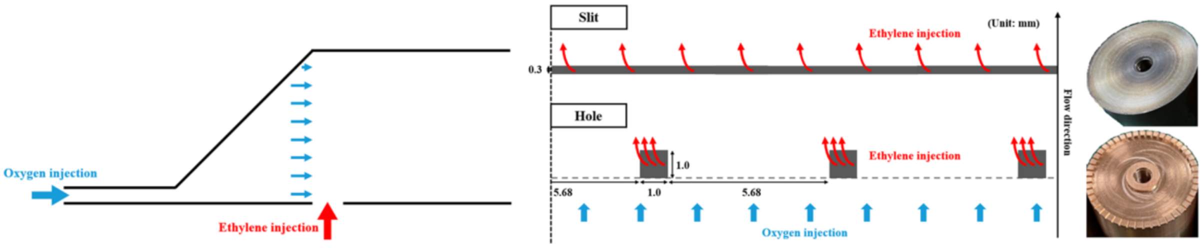

Fig 3. Fuel injection structure and experimental injector models

3. Experiment result

The experimental conditions for the hole-type fuel injector were set to penetrate after 5 mm of the RDE channel in the longitudinal direction up to the RDE outer wall. The corresponding jet momentum ratio for this configuration was maintained below 3.0. The jet momentum ratio was calculated using the measured fuel and oxidizer pressure values obtained from the experiments using the hole-type injector. The pressure values and calculated jet momentum ratios for each experiment denoted in Table 1.

Table 1. Experiments conditions and jet momentum ratio

Exptl. Num.	P_{0,GO_2} (MPa)	P_{0,GC_2H_4} (MPa)	J
01	0.367	0.241	2.665
02	0.356	0.242	2.675
03	0.536	0.234	2.812

3.1. Experiment sequence

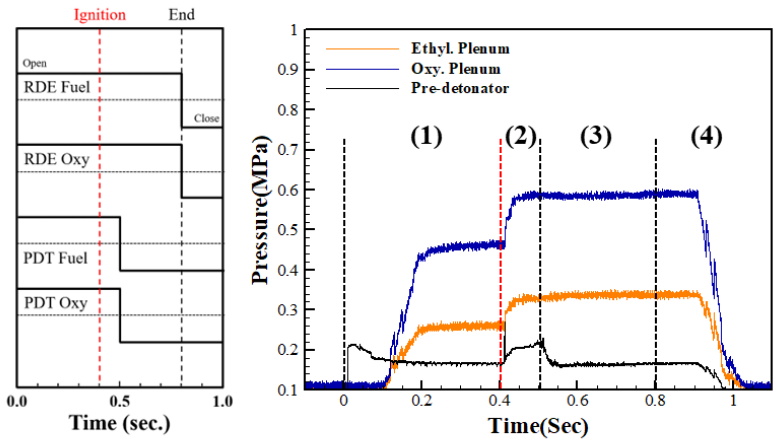

Fig 4. Pressure history in fuel, oxygen, and pre-detonator according to the experimental sequence

Fig. 4 represents the experimental sequence. The details of the experiment sequence are as follows: (1) The pneumatic valve was opened to supply propellant to the RDE, simultaneously, the solenoid valve was opened to supply it to the pre-detonator. (2) The pre-detonator operated, and combustion began inside the RDE chamber. (3) Combustion experiment of the rotating detonation engine proceeded for 0.4 seconds from ignition. (4) All valves were closed, and the experiment was concluded. Due to the residual propellant in the pipeline, high-pressure history was maintained for a short period.

3.2. Summary of the combustion experimental result

The list of conducted experiments is provided in Table 2. The experiments were primarily conducted at a low flow rate of 40~70 g/s. The equivalence ratio was calculated based on the measured flow rates, and the detonation velocity was determined through FFT analysis. The number of detonation waves was recorded using a high-speed camera and FFT analysis. From the experimental results, it can be observed that in all experiments, two detonation waves propagated. However, in only one experimental case (in Num. 8), a transition from a 2-wave mode to a 3-wave mode occurred. The detonation velocity, which is a function of calorific value, was found to be more than 10% higher for the hole-type fuel injector compared to the slit-type fuel injector. This result suggests that the hole-type injector exhibits better fuel mixing performance due to the influence of side recirculation and counter-rotating vortex pair, in contrast to the two-dimensional effect of the slit-type injector.

Table 2. Summary of the experimental result

Case	**Exptl. Num.**	$\dot{m}$ (g/s)	Φ	**Wave num.**	$V_{detonation}$ (m/s)
Slit	1	31.26	1.44	2	1,475
	2	43.20	0.86	2	1,514
	3	42.25	0.86	2	1,504
	4	58.97	1.03	2	1,498
Hole	5	41.13	1.11	2	1,677
	6	44.41	0.99	2	1,677
	7	44.13	0.86	2	1,678
	8	74.11	1.02	2 or 3	1,669

3.3. Analysis of the primary results

For a more accurate comparison, experiments with similar conditions, such as Num. 2 and 7, were examined. The two experiments have similar mass flow rate and same equivalence ratio. The only difference between these two cases is the injector configuration. In both cases, the wave numbers were in the 2-wave mode, but there was a difference between the FFT results and the detonation velocity. The results of the two experiments were presented in Fig. 5.

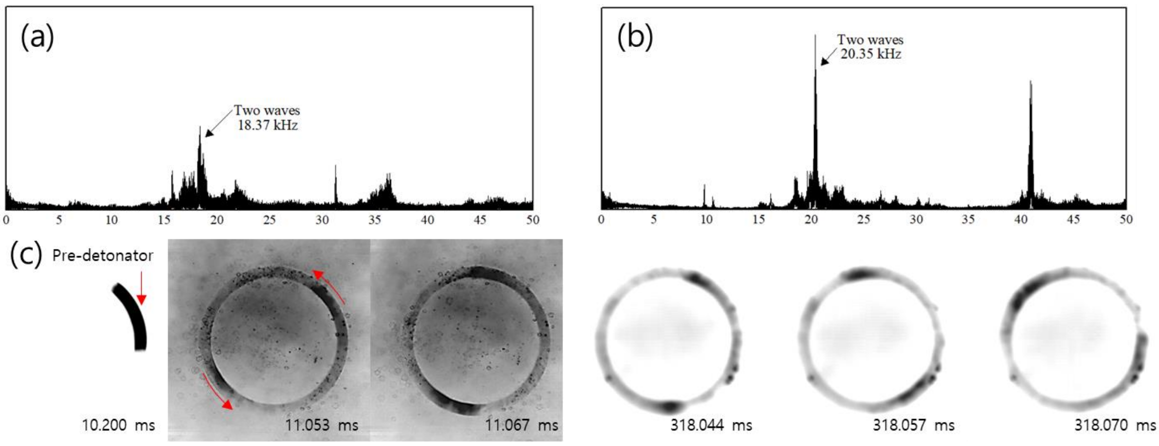

Fig 5. Experiment results: (a) The FFT analysis for Exptl. Num. 2
(b) The FFT analysis for Exptl. Num. 7 (c) High-speed camera snapshot of the 2-wave mode results

When high-speed camera recordings were performed for both experiments, they exhibited the same pattern as shown in Fig. 5 (c). However, the peak frequencies observed during FFT analysis were different from each other. In the slit-type injector, two detonation waves were maintained, and the FFT analysis showed the detonation rate of about 18 kHz. This was converted to the detonation velocity of approximately 1,500 m/s and was measured at a lower velocity than the hole-type injector. In the hole-type injector, similar to the slit-type injector, two waves were rotated, but the detonation velocity was generally higher overall. The FFT results indicated the detonation rate of approximately 20 kHz, which was converted to the detonation velocity of over 1,600 m/s. Exptl. Num. 2 and 7 only differed in the shape of the injector. Therefore, it can be concluded that the improved fuel mixing performance due to the difference in injector configuration led to an approximately 10% higher detonation velocity.

Additionally, exptl. Num. 4 and 8, which were conducted with relatively high mass flow rates, were compared. In both cases, there was a difference in the supplied mass flow rates, but the equivalence ratio was similar. The results for these were presented in Fig. 6.

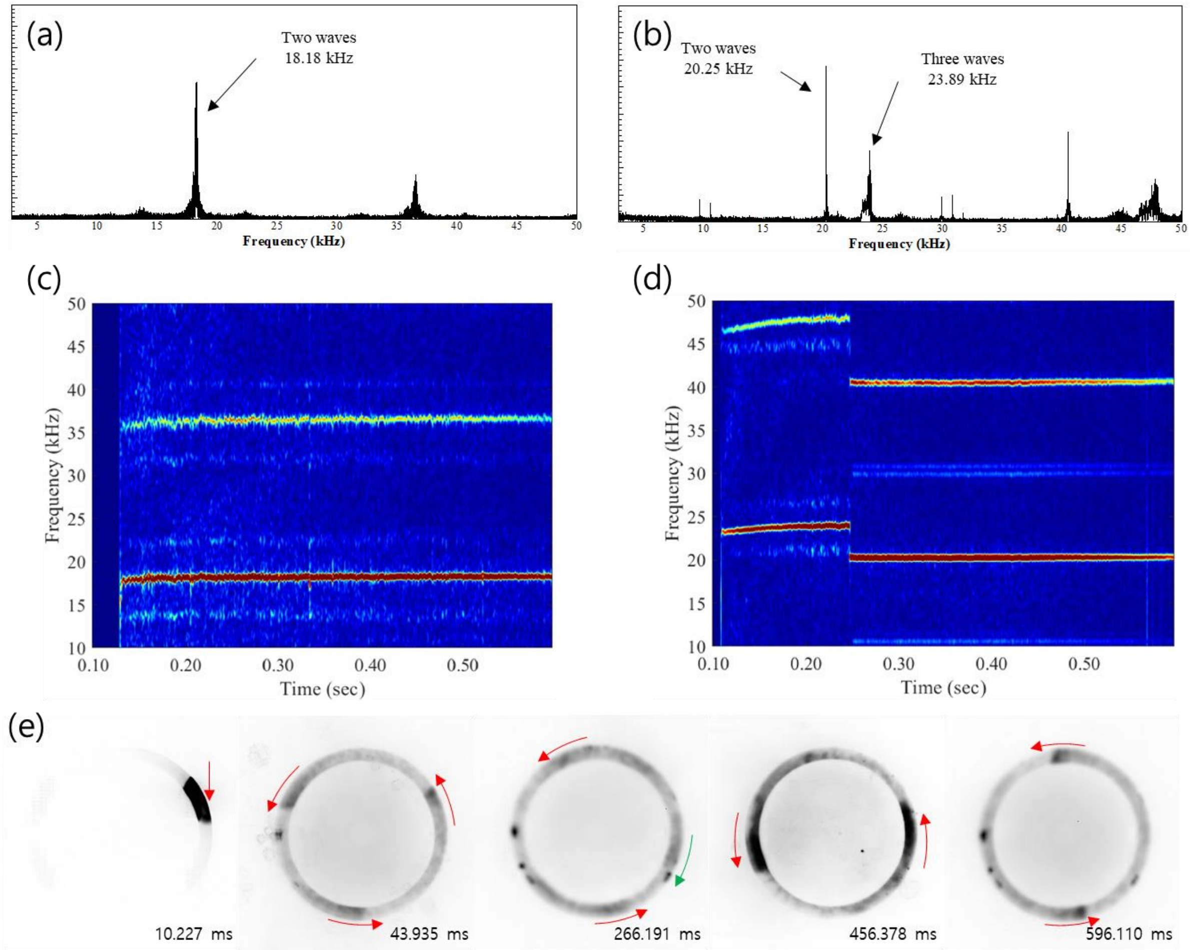

Fig 6. Experiment results: (a) The FFT analysis for Exptl. Num. 4
(b) The FFT analysis for Exptl. Num. 8 (c) The STFT analysis for Exptl. Num. 4
(d) The STFT analysis for Exptl. Num. 8 (e) High-speed camera snapshot of the 2-wave mode results

Table 3. Comparison of the results for experiment Num. 4 and 8

Case	**Exptl. Num.**	$\dot{m}$ (g/s)	Φ	**Wave**	$V_{detonation}$ (m/s)	**Thrust** (N)
Slit	4	58.97	1.03	2	1,498	82.7
Hole	8	74.11	1.02	2	1,669	82.7
		-	-	3	1,313	-

Similar to the previous experimental results, Num. 4 exhibited the similar detonation propagation velocity, and the number of waves was also consistent at 2-wave. On the other hand, Num. 8 transitioned from the 3-wave propagation mode to the 2-wave propagation mode. In the 3-wave propagation mode, a significantly low detonation velocity was obtained. Especially in the STFT results, a clear difference in detonation rate can be observed when transitioning from the 3-wave mode to the 2-wave mode. Furthermore, the 3-wave mode was sustained only for a short period of time initially. However, Due to the response time of the mass flow meter and loadcell, there is a limit in that the mass flow rate and thrust at 3 wave mode could not be measured. Due to the relatively increased flow rate, three waves may have propagated initially, but due to factors such as imbalance in mass flow rate caused by the injector or supply system, it could have transitioned to a two-wave mode. To understand the exact reasons behind these phenomena, additional experiments will be necessary.

The 2-wave propagation mode persisted for a relatively long period, enabling sufficient comparison with other experimental results. In the hole-type injector, when in the 2-wave mode, it exhibited a higher detonation rate and detonation velocity compared to the slit-type injector. On the contrary, in num. 8, despite an increase in flow rate, the thrust remained the same as in exptl. num. 4 and 8. Thus, despite the increase in flow rate, the thrust remained constant, resulting in a lower calculated specific impulse. Due to the short experimental duration, there are limitations to the accuracy of the analysis. Additionally, it can be speculated that the transition from the 3-wave mode to the 2-wave mode may have an impact on the performance. Due to the low sampling rate of the load cell and mass flow meter, these limitations have arisen. Further analysis is required to understand the reasons behind these results.

4. Conclusions

Experimental research was conducted on an Annular-type Rotating Detonation Engine (RDE) using gaseous ethylene and gaseous oxygen as propellants. A comparative study was performed to investigate the improvement of fuel mixing efficiency by comparing a hole-type fuel injector, which has a 3-dimensional effect, with the slit-type fuel injector known for its 2-dimensional effect. The calculation of fuel injection height was based on the similarity of fuel injection to a scramjet. An equation expressing the pressure relationship between the fuel and oxidizer, capable of achieving a jet momentum ratio of 3.0, was derived, and combustion experiments were conducted. Detonation velocities were determined through FFT analysis, confirming performance improvement. However, when the 3-wave to 2-wave propagation mode changed, it was difficult to conduct an accurate performance analysis. Further analysis on this phenomenon will be conducted through future experiments.

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