Effect of Injector Arrangement in Disk-type Rotating Detonation Engine

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1 Introduction

The concept of utilizing fuel detonative combustion for propulsion was first introduced by Ya.B. Zeldovich in 1940, who analyzed the efficiency of the detonation cycle [1]. According to his analysis, the detonation cycle offers approximately 20% higher efficiency than the Brayton cycle. This seminal work marked the beginning of efforts to integrate detonation into engines, leveraging its substantial efficiency benefits. Since then, extensive research has been dedicated to the development of detonation-based propulsion systems.

There are two primary types of detonation-based engines: Pulse Detonation Engine (PDE), which generates thrust through intermittent detonation, and Rotating Detonation Engine (RDE), which maintains a continuous detonation wave rotating within the combustor to produce thrust. The PDE operates on a periodic cycle, requiring intermittent ignition, whereas the RDE achieves continuous thrust by sustaining detonation once ignited and supplying a steady flow of propellants. This continuous operation is expected to enhance efficiency significantly. Moreover, RDEs offer structural advantages beyond their high theoretical thermal efficiency. The self-pressurization induced by shock waves during detonation can replace the compression work typically performed by compressors or turbopumps, enabling substantial reductions in combustor size and weight.

The combustion chambers of RDEs are generally classified into three main types: annular structure [2], hollow structure [3], and disk-shaped structure [4]. Among these, the annular structure was the first model proposed and remains the most studied RDE configuration. In this design, propellants are supplied axially along the chamber, with combustion gases expelled in the same direction. However, due to the complexity and high-speed nature of phenomena occurring within the chamber, observing the three-dimensional propagation of detonation waves in RDEs has proven to be highly challenging.

Nakagawa et al. [4] addressed this issue by shortening the chamber size and adopting a disk-shaped configuration, successfully visualizing the injection jet structure and the behavior of rotating detonation waves. Furthermore, according to NASA [5], the disk-shaped structure demonstrated higher pressure gain (PG) compared to the annular structure. This finding highlights the potential of disk-type RDEs (DRDEs) to achieve both combustor miniaturization and effective pressure gain combustion (PGC). Several studies on DRDEs have been conducted in recent years [6-11]. In these studies, injector configurations are typically designed to ensure efficient mixing of fuel and oxidizer. Common

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configurations include the Facing-type, where injectors are positioned directly opposite each other, and configurations where injectors intersect at right angles. While some studies [12,13] have investigated the effects of injector configurations RDEs, limited research has examined the impact of varying injector arrangements in DRDE experiments. This study aims to investigate the influence of injector configurations on the behavior of rotating detonation waves in DRDEs by comparing the conventional Facing-type alignment with a novel "Gear-type" configuration, where injectors are offset, resembling interlocking gears.

2 Experimental setup

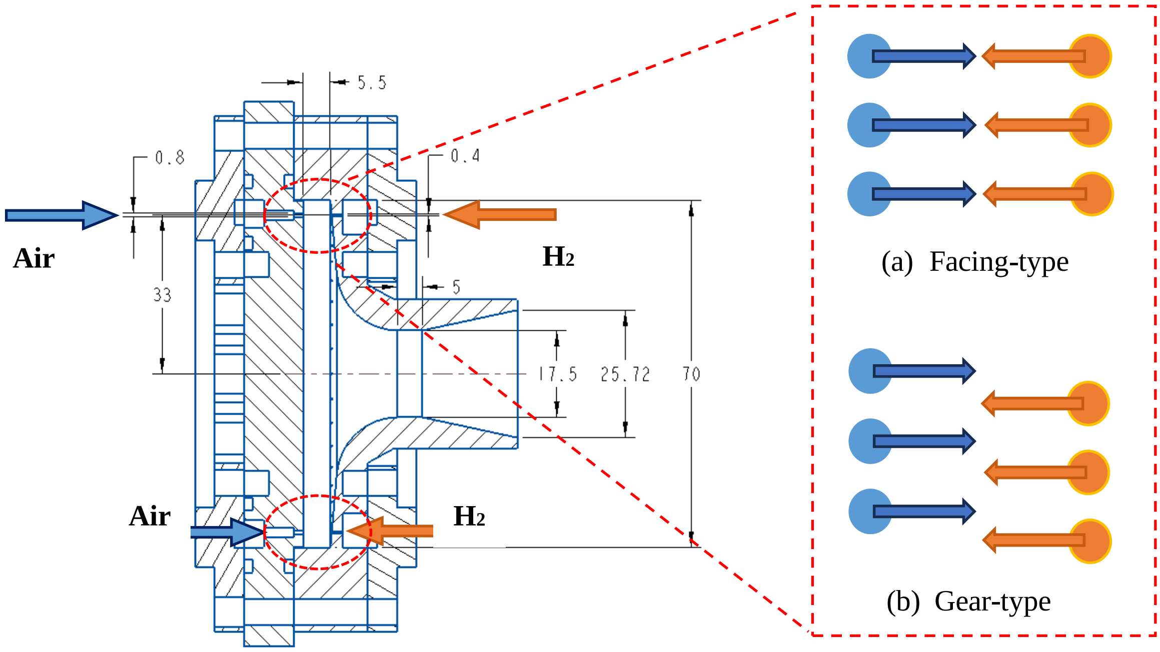


Figure 1: (Left) Cross-section of the DRDE, (Right) injector arrangements: (a) Facing type, (b) Gear type

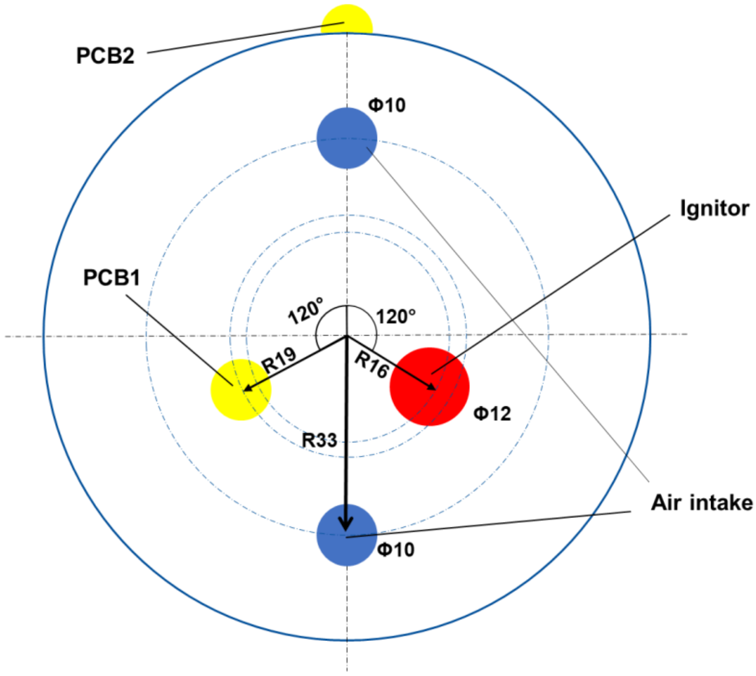


Figure 2: PCB arrangements (Back view)

The DRDE chamber is illustrated in Fig. 1. Hydrogen is used as the fuel and is supplied axially through 40 orifices, each with a diameter of 0.4 mm. Similarly, air is employed as the oxidizer and is supplied axially through 40 orifices, each with a diameter of 0.8 mm. The right side of Fig. 1 depicts the arrangement of the fuel and oxidizer inlets. (a) In the Facing-type configuration, hydrogen and air jets collide with each other to get uniform mixtures. (b) In the Gear-type configuration, the components are arranged with a 30-degree phase shift relative to the Facing-type, resulting in an alternating hydrogen supply and air. The detonation is initiated by an initiator located near the circumference of the chamber. A stoichiometric H_2/O_2 mixture is preloaded into the chamber and ignited by a spark plug at the end of a small tube, propagating the detonation wave into the chamber.

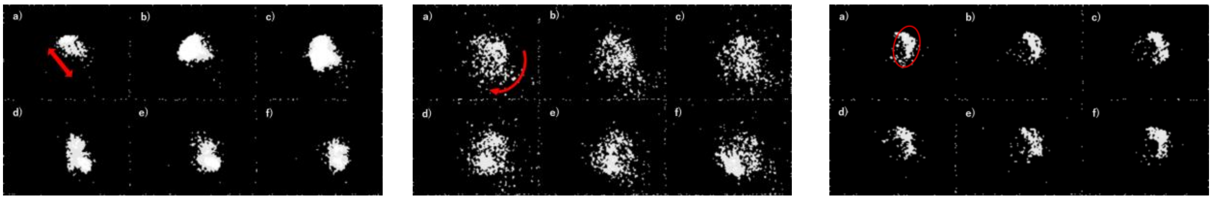
Figure 2 illustrates the arrangement of pressure sensors. The behavior of the rotating detonation within the chamber is monitored using three pressure sensors (PCB 113B24), designated as PCB1, PCB2, and PCB3. PCB1 and PCB2 are installed on the rear surface of the engine with a phase difference of 120°, while PCB3 is mounted on the outer circumference of the engine and is in phase with PCB1.

To measure the detonation velocity and analyze the combustion mode, a high-speed camera (FASTCAM Nova S6) captures images of the chamber from the nozzle side. The frame rate of the high-speed camera is set to 200,000 fps, with an exposure time of either 5 µs or 2.5 µs. A summary of all test conditions is presented in Table 1.

Table 1: test conditions

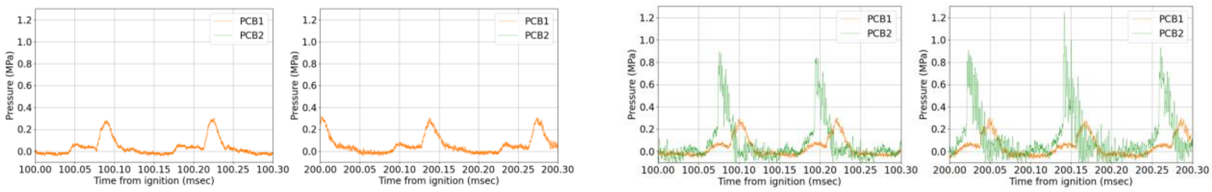
Injector-type	Mixture Mass flow rate [g/s]	Equivalence ratio Φ [-]	Combustion time [s]
Facing	32 ± 2.0	0.8-2.4	0.3
Gear	33 ± 2.0	0.8-3.1	0.3

3 Results

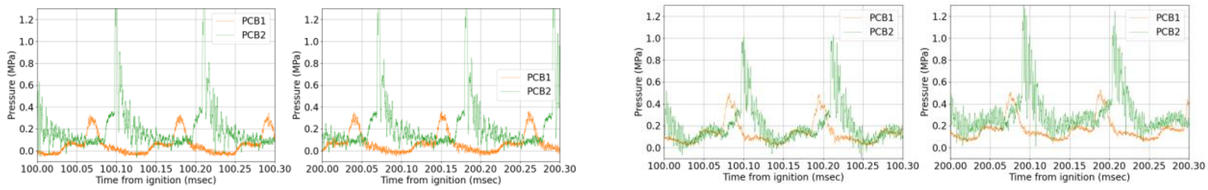


(I) Tangential mode (II) Single wave mode (III) Dual wave mode

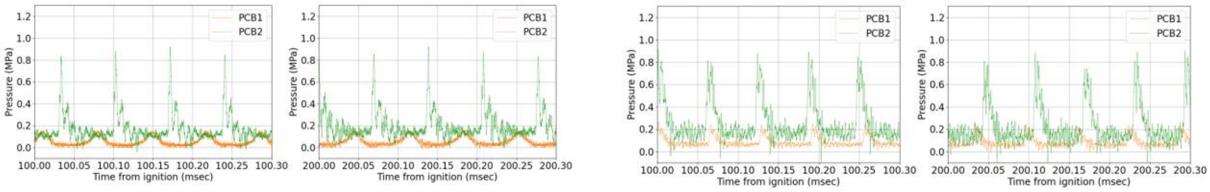
Figure 3: Time sequences of each detonation mode from a) to f)



(I): (Left) Facing-type ($\emptyset = 0.98,\ \dot{m} = 31.62\ g/s$), (Right) Gear-type ($\emptyset = 1.21,\ \dot{m} = 33.08\ g/s$)



(II): (Left) Facing-type ($\emptyset = 1.54,\ \dot{m} = 32.29\ g/s$), (Right) Gear-type ($\emptyset = 1.35,\ \dot{m} = 33.41\ g/s$)



(III): (Left) Facing-type ($\emptyset = 1.17,\ \dot{m} = 32.05\ g/s$), (Right) Gear-type ($\emptyset = 3.05,\ \dot{m} = 35.09\ g/s$)

Figure 4: Pressure histories of each detonation mode

Figure 3 illustrates the three types of detonation waves observed in this experiment. The white luminous regions correspond to the detonation waves, while the red circles indicate the view area and the nozzle outer edge. In Ref. [8], the authors installed a polycarbonate channel plate on the nozzle side to observe the propagation of detonation waves. They identified two propagation modes: the Single wave mode and the Dual-wave mode. In our experiments, in addition to these modes, we also observed a Tangential mode. As shown in Fig. 3 (II) Single wave and (III) Dual wave, the detonation wave could not be clearly observed within the view area. This suggests that the detonation wave propagates along the outer circumference of the combustion chamber. This result is consistent with the results reported by Ishii et al. [11]. One possible explanation for this behavior is the inlet area ratio $A_{3.1}/A_{3.2}$, where $A_{3.1}$ represents the minimal air inlet area, and $A_{3.2}$ corresponds to the combustion chamber cross-sectional area. In the experiment conducted by Ishii et al., the inlet area ratio was set to 0.1, while in the present experiment, $A_{3.1}/A_{3.2}$ was 0.10059. Given the close agreement between these values, this result is in good agreement with that of Ref. 11. Figure 4 illustrates the pressure histories of each detonation mode for different injector configurations. In the graph corresponding to the Facing-type configuration in the Tangential mode (I), data from PCB2 could not be acquired due to an error. However, across all configurations from (I) to (III), the Gear-type graphs exhibit significant pressure oscillations. This suggests that the Gear-type configuration induces greater flow disturbances, resulting in less stable combustion and detonation behavior.

Figure 5 presents the propagation velocity of the observed detonation modes normalized by the Chapman–Jouguet (CJ) detonation velocity, with the equivalence ratio on the horizontal axis.

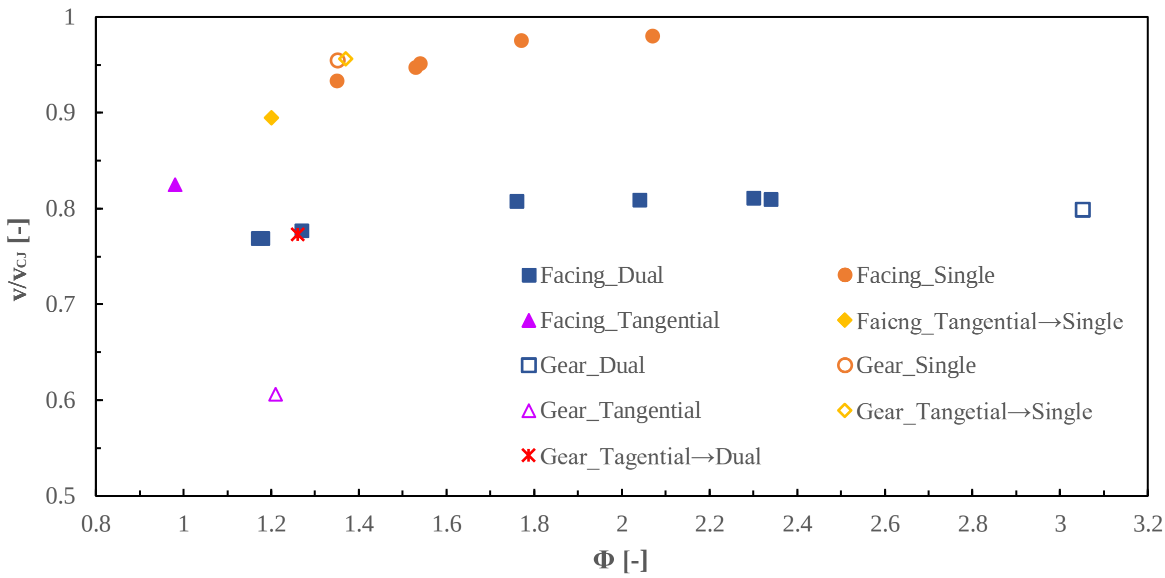


Figure 5: Comparison of Detonation Mode Velocities Normalized by CJ Speed under Each Injector Configurations

In the Gear-type configuration, detonation occurred only 5 times out of 25 experiments, of which 3 were identified as transition modes, indicating the instability of detonation in this configuration. In the Facing-type configuration, for both the single wave and dual wave modes, the propagation velocity increases as the equivalence ratio approaches 2, suggesting a proportional relationship between equivalence ratio and propagation velocity. Furthermore, an increase in the number of waves corresponds to a decrease in propagation velocity, which is consistent with the experimental results reported by Zhenjuan Xia et al [14].

4 Conclusion

In this study, we conducted experiments by varying the injector arrangements for the oxidizer and fuel sides in a DRDE, specifically comparing the Facing-type and Gear-type configurations. As shown in Fig. 4, the Gear-type configuration exhibited greater overall oscillations compared to the Facing-type configuration, suggesting a negative impact on detonation stability. Furthermore, Figure 5 indicates that there was no significant difference in the propagation velocities among the various injector configurations. However, in the present study, 25 tests were conducted for each injector configuration, and detonation was observed 14 times in the Facing-type configuration, whereas only 5 detonations were observed in the Gear-type configuration. These results indicate that the injector configuration has a significant influence on both the stability and the initiation conditions of detonation.

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