

# Experimental Investigation of Hollow-Body Ramjet Rotating Detonation Engine for Hypersonic Propulsion

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## Abstract

Rotating detonation engines (RDEs) are an emerging propulsion technology with the potential to transform high-speed atmospheric flight systems by offering significant thermodynamic efficiency improvements over traditional deflagration-based combustors. Unlike deflagration, which relies on subsonic flame propagation, RDEs utilize supersonic shock-flame complexes that compress fuel-oxidizer mixtures ahead of reaction zones, enabling higher pressure and energy release. The hollow-body RDE design presents advantages in reducing structural weight and eliminating the need for complex cooling systems, making it a promising candidate for hypersonic propulsion applications. This study investigates the performance of a hollow-body, air-breathing RDE configured for ramjet operation. Experiments were conducted using a high-enthalpy blowdown wind tunnel simulating Mach 4 flight conditions with a stagnation temperature of 1200 K and mass flow rates of 1.16–1.24 kg/s. A hydrogen-air mixture served as the fuel-oxidizer combination. High-speed broadband chemiluminescence imaging confirmed the formation of a stable rotating detonation wave (RDW) propagating at a detonation wave speed of 1200 and 1260 m/s, corresponding to 60% and 63% of the theoretical Chapman-Jouguet (CJ) detonation velocity ( $D_{CJ}$ ), respectively. Static pressure measurements recorded at kHz frequencies demonstrated pressure gains consistent with theoretical predictions, with the RDW exhibiting comparable performance to those observed in annular configurations.

## 1 Introduction

RDEs represent an innovative propulsion technology with the potential to revolutionize the efficiency and design of high-speed atmospheric flight systems. Conventional combustors utilize deflagration combustion, generally characterized by subsonic flame propagation that results in a decrease in pressure and density [1]. In contrast, detonations involve a shock wave followed by a reaction front which travels at sonic or supersonic speeds. Detonations also produce higher temperatures, pressures, and densities than deflagration reactions. These differences between combustion regimes lead to significant differences in engine performance, with detonations offering higher thermodynamic efficiency compared to deflagration-based cycles [1,2]. This efficiency advantage, along with other performance improvements, motivates ongoing studies into the application of detonative combustion in novel propulsion systems.

RDEs utilize one or more continuously rotating detonation waves (RDWs) propagating circumferentially around a cylindrical combustor where reactants are continuously fed into the system [1–3]. Initial observations of spinning detonations were conducted by Voitsekhovskii et al. with gaseous acetylene and oxygen [4]. RDEs configured in a ramjet mode are a promising means of powering hypersonic flight vehicles. Because ramjet RDEs typically operate with high freestream temperature and velocity, RDW establishment is often challenging. Braun et al. performed a cycle analysis of an air-breathing RDE for up to Mach 5 flight with hydrogen and propane fuels [6]. Subsequent two-dimensional [7] and three-dimensional [8, 9] numerical modeling by Zhdan and Rybnikov demonstrated the establishment of an RDW in an annular combustor for high flight velocities up to Mach 4. Following these numerical studies, researchers sought to explore ramjet RDEs experimentally. Wang et al. experimentally validated the establishment of an RDW in an air-breathing ramjet configuration using hydrogen fuel in an annular combustor [10], with Frolov et al. observing similar results with a hydrogen-air mixture [11].

While a significant amount of research has been performed exploring ramjet RDEs with various fuels, prior numerical and experimental investigation focus primarily on annular combustor architectures. However, annular combustors pose challenges for operation over long durations, making hollow-body rotating detonation combustors (RDCs) attractive for engine design. Tang et al. first numerically validated the feasibility of a hollow-body geometry, comparing the results to a typical annular combustor [12]. This discovery led to an experimental study by Lin et al. where an RDW was established in an hollow combustor using methane and oxygen [13]. Anand et al. investigated the performance of a hollow-body, air-breathing RDC with hydrogen fuel [14]. Subsequent studies also explored hollow-body RDEs, with these studies all being performed using a rocket configuration.

Due to its reduced weight and lack of required inner-body cooling, the hollow-body RDE has strong potential for applications in high-speed flight vehicles. However, no current experimental research exists for a hollow-body RDE operating in a ramjet mode. This study presents experiments performed using a hollow-body RDC. The RDC is attached to a high-speed, high-enthalpy blowdown wind tunnel facility which is used to simulate Mach 4 flight conditions, although static pressure measurements indicated that flow was subsonic in the RDC. Additionally, high-speed broadband chemiluminescence was recorded to validate RDW establishment and obtain a quantitative measurement of detonation wave speed, and the wave speed is compared to prior ramjet RDE studies with annular combustors.

## 2 Experimental Methodology

The research was conducted using the High-Enthalpy Hypersonic Reacting (HyperReact) Facility at the Propulsion and Energy Research Laboratory at the University of Central Florida (UCF) [15]. The facility, shown in Fig. 1 consists of three major components—in order of location axially along the facility, an in-flow air preheater, a converging-diverging (CD) nozzle, and an RDE test section. The air preheater is used to simulate flight enthalpy by increasing the mixture stagnation temperature. A spark plug is used to ignite a coaxial hydrogen-air jet burner that is surrounded by four co-flow air jets. This preheater is capable of generating flows with stagnation temperatures of 800-2000K and stagnation pressures of 300-1300psi. Following the flame burner is a 45x45mm square channel for mixing with a length of 350mm, which allows the vitiated mixture to homogenize.

Additionally, the air supply is enriched with additional oxygen prior to experimental testing to more accurately mimic flight-relevant conditions. Because a portion of the oxygen available in the air will be consumed, the additional oxygen ensures that the vitiated mixture has an oxygen mole fraction of 21%, the same as in dry air. The number of moles of oxygen that will be consumed by the preheater flame is predicted using Cantera with the FFCM-2 reaction mechanism [16] and assuming complete combustion of hydrogen fuel. Thus, that amount of oxygen can be added to dry air for experiments.

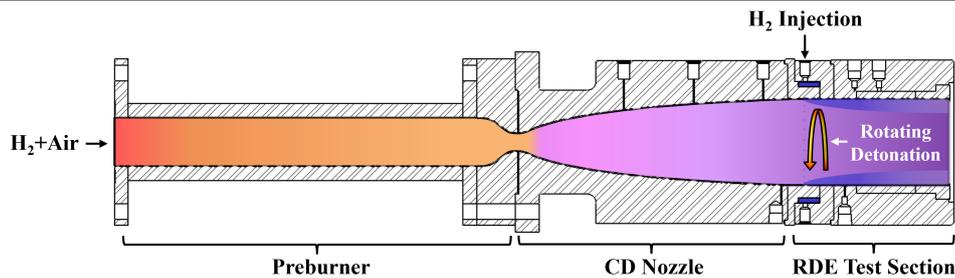


Figure 1: Schematic of HyperReact facility with RDE test section

The vitiated mixture flows downstream into an axisymmetric CD nozzle that accelerates the flow to supersonic velocities. The CD nozzle was designed with an exit-to-throat area ratio of 21.88, providing a flow Mach number of 4.88 for dry air at 300K. Because the geometry of the nozzle is fixed, the flow Mach number varies from 4-4.32 depending on the temperature and specific heat ratio of the vitiated mixture supplied by the preheater.

After the mixture is accelerated, the high-speed flow enters the RDE test section with a constant diameter of 80mm. First, a fuel injector array supplies fuel immediately downstream of the nozzle. The array consists of 72 flush wall-mounted injectors, each with a diameter of 0.41mm, and the injectors are oriented normal to the crossflow and equally spaced circumferentially about the test section. This configuration produces a fuel-rich region along the test section wall within which the reaction occurs. A hydrogen-oxygen predetonator is positioned axially downstream and fires tangentially to cylindrical wall in order to initiate a detonation.

A series of Omega PX309 absolute pressure transducers recording at a rate of 10kHz and with a range 0-689.48kPa were positioned along the wall of the CD nozzle and test section. The pressure transducers, along the CD nozzle were used to validate flow expansion and observe any potential shocks that form in the nozzle while the test section pressure transducers were employed to observe pressure gain in the combustor.

High-speed broadband chemiluminescence was used to visualize the RDW phenomenon. Imaging was obtained using a Photron SAZ recording at 21kHz with a resolution of 512x576 pixels, and the exposure time was set to 47.6 $\mu$ s. A flat mirror is placed downstream of the facility at an angle relative to the exhaust flow, and the camera is positioned off-axis to record the reflected image. A long focal length lens was used to resolve the experimental test section in the field of view. A quantitative measurement of detonation wave speed was determined using the image post-processing technique described by Bennewitz et al. [17].

### 3 Results and Discussion

Two experimental test cases were conducted, with Table 1 outlining the conditions of each test. The mass flow rates of the vitiated air varied between 1.1-1.2kg/s, with the air preheater being used to raise the stagnation temperature of the vitiated mixtures to approximately 1200K. This temperature was chosen to mimic Mach 4 flight conditions at 20km. Additionally, the corresponding test section equivalence ratio of the two tests were 0.72 and 0.74, respectively. In both test cases, an RDW was established in the combustor.

The experiments conducted in this study demonstrate the successful establishment of an RDW in a hollow-body ramjet combustor. Static pressure measurements indicated a test section Mach number of

Table 1: Experimental test conditions

Test Number	$P_0$ (MPa)	$T_0$ (K)	$\dot{m}_{air}$ (kg/s)	$\phi_{TS}$
1	2.78	1160	1.20	0.72
2	2.62	1200	1.13	0.74

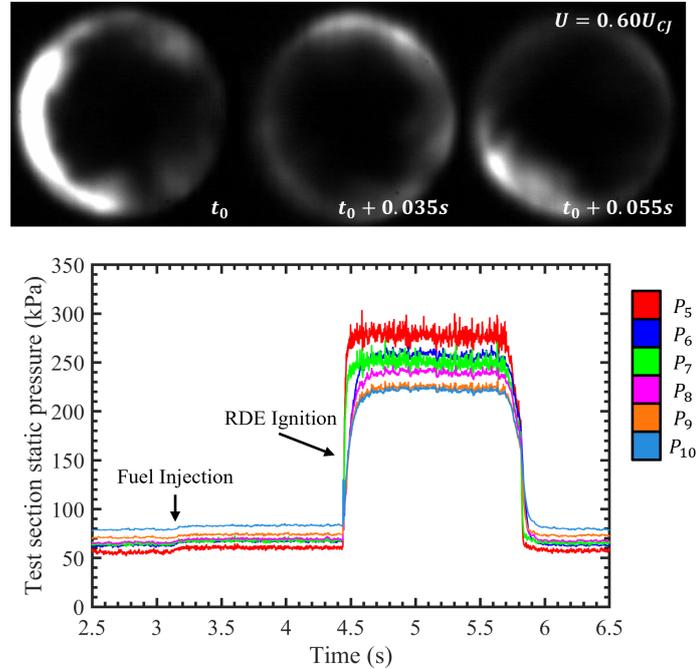


Figure 2: High-speed off axis imaging of RDW establishment

approximately 0.56 which corresponds to a freestream velocity of 373 and 380m/s. High-speed broadband chemiluminescence, shown in Fig. 2, indicated that a single RDW propagated counterclockwise along the combustor wall. From post-processing of the imaging, the detonation wave speed for the first and second test cases were found to be 1200 and 1260m/s, respectively. This results in a ratio of wave speed to  $D_{CJ}$  of 0.6 and 0.63 which is a similar finding to that of prior ramjet RDE experiments with annular combustor geometries [18].

From the static pressure measurements, a steady pressure rise was observed as a result of combustor ignition. Figure 3 shows pressure transducer positions, both axially along the flow direction and angularly with respect to the facility exhaust, on the wall of the RDE test section and the associated static pressure measurements over the duration of the experiment. While a slight increase in static pressure was observed due to shocks generated by hydrogen fuel injection, all pressure transducers recorded a steady pressure rise of nearly six times the non-reacting flow pressure during RDE operation.

However, when viewing the static pressure measurements with respect to the axial position of the pressure transducers, a pressure rise was observed in the nozzle, upstream of the reaction. Figure 3 shows the static pressure measured axially from the inlet plane of the CD nozzle at different points in the experiment. The pressure measurements along the wall of the nozzle show expected flow behavior through the nozzle during the cold flow and fuel injection periods of the experiment, demonstrating that the vitiated air flow was supersonic prior to RDE ignition. However, while combustion occurs in the test section, the static pressure increases through the diverging section of the nozzle, indicating that freestream is subsonic in the test section.

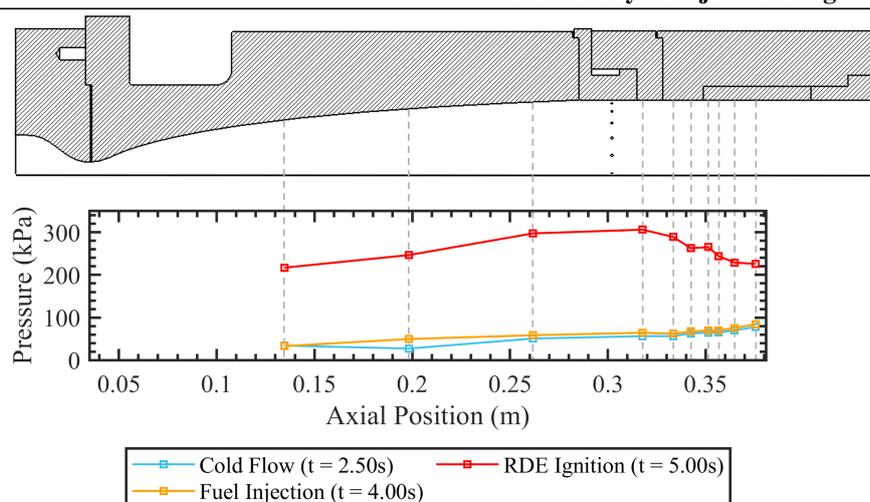


Figure 3: Static pressure measured axially from the inlet plane of the CD nozzle

## 4 Conclusions

This study has successfully demonstrated the feasibility and performance of a hollow-body, air-breathing operating in a ramjet configuration under simulated Mach 4 flight conditions at 30km. A hydrogen-fueled rotating detonation combustor integrated with a high-enthalpy wind tunnel, operating with stagnation temperatures of 1200 K and mass flow rates between 1.16 and 1.24 kg/s. The experiments demonstrated the establishment of a stable RDW propagating at 1200 and 1260 m/s, representing 60% and 63% of  $D_{CJ}$ , respectively. Additionally, static pressure measurements revealed significant pressure gain during RDC operation, highlighting the efficacy of the detonation-based combustion process. The observed wave speeds and pressure gains align closely with previous studies ramjet RDEs with annular combustor architectures, confirming that a hollow-body ramjet RDE can achieve comparable performance. This research highlights the potential of hollow-body, air-breathing ramjet RDEs to overcome the limitations of conventional annular configurations and achieve high performance in hypersonic propulsion applications.

## 5 Acknowledgments

This work is sponsored by the Air Force Office of Scientific Research (FA9550-16-1-0441 and FA9550-19-1-0322, Program Manager Dr. Chiping Li).

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