Experimental Study of a High Pressure Rotating Detonation Wave Combustor for Rocket Applications

Stephen Heister², David Stechmann¹, and Dasheng Lim¹
Purdue University, West Lafayette, IN, 47906

Abstract
Rotating Detonation Engines (RDEs) represent a promising technology for increasing the specific impulse of rocket combustors, however more research is needed to quantify the real-world performance of these devices and understand how they can be optimized for use at high-pressure conditions. To this end, Purdue University has developed a high-pressure experimental RDE under AFOSR sponsorship with an oxygen-rich pre-burner capable of operating on liquid methane and liquid oxygen at flow rates up to 9 lbm/sec (4.1 Kg/sec) and mean chamber pressures up to 1200 psi (8.3 MPa). Project funding was initiated in September of 2014. Prior to fabricating the experimental hardware, analysis was undertaken in an effort to understand and quantify overall system flow behavior, injector mixing time lag, injector transient response, and thermal-structural loading. Testing begin in May 2015 with hydrogen, though a transition to higher flow rates with liquid methane is expected in late 2015. Ignition and combustion behavior are reliable and consistent in all tests to date with thrust values reaching approximately 85% of theoretical values. Continuous detonation has not been consistently achieved however and the chamber thermal environment has been especially challenging for instrumentation, so additional design revisions and tests are ongoing.

1. Motivation and Test Article Description

Rotating Detonation Engines (RDEs) represent a promising technology for achieving the goal of appreciably increasing rocket engine specific impulse. RDEs are a type of pressure-gain combustion device where most of the combustion takes place in high-pressure detonation waves traveling tangentially around an annular combustion chamber. RDEs can potentially reduce required combustor volume and increase delivered specific impulse by up to 13% (as shown in Figure 1 for methane and oxygen propellants) while avoiding many drawbacks associated with other pressure-gain combustion concepts (including Pulse Detonation Engines). The engineered transient nature of RDEs may also make it possible to avoid unexpected combustion instability during chamber development. This would be a significant boon to engine manufacturers.

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¹ Graduate Student, School of Aeronautics and Astronautics
² Present Address: NASA Glenn Research Center, Cleveland, OH, 44135
2. Design and Operating Parameters

The heat-sink cooled RDE subassembly is shown in detail in Figure 2. Precision alignment pins are employed on the outer and inner components to ensure consistent flow-path area around the annulus once all components are assemble. The inner alignment pins are ported to provide a vent flow-path for the back-side of the internal seals. A straight convergent flow-path from the pre-burner, through the center support struts, and through the fuel injector is employed for the oxidizer to minimize pressure losses and flow turbulence associated with turning the high volumetric flow rate from the pre-burner. As shown in Figure 2, this path converges through a narrow annular choke just prior to entering the main detonation channel. Fuel is injected just upstream of this choke through 120 0.02” diameter holes to provide fast mixing and vaporization of the fuel and oxidizer in the high velocity gas flow.

![Figure 2: Perspective and section views of the RDE subassembly.](image)

An additional important area of the RDE design relates to instrumentation and data acquisition. While thorough data acquisition is important for characterizing RDE performance and operating behavior, a minimum instrumentation suite was employed in the test hardware until initial testing could be completed. This minimal instrumentation suite consists of a CTAP (capillary tube averaged pressure) for measuring the mean detonation channel pressure, a flush-mounted PCB transducer for measuring high-frequency pressure response in the detonation channel, an flush-mounted ion-gage for measuring high-frequency flame front propagation in the detonation channel, load cells for measuring axial thrust, a calibrated microphone for evaluating the engine and exhaust acoustic signature, a high-speed camera and mirror assembly for viewing combustion through the nozzle, and low-speed cameras for taping and photographing the test and exhaust plume.

5. Test Results

As of this writing, 35 RDE and pre-burner tests have been completed (most of these being hot-fire tests). While the test article was designed for use with liquid methane, all of these tests were conducted using gaseous hydrogen instead to establish a baseline before moving to a more difficult fuel. Starting with hydrogen also made it possible to test sooner due to the easier facility integration. Due to the very different densities between hydrogen and liquid methane, a new center-body was built for these tests. This new center-body was designed to reduce the channel and throat width to 0.12” (3.05 mm) and 0.053” (1.35 mm) respectively.

It is clear from the first set of hot-fire tests that the pre-burner and torch ignition system function as intended. In general the test sequence begins by purging the hardware with nitrogen, flowing liquid oxygen through the pre-burner to chill the manifold, purging with nitrogen again, and then starting the pre-burner torch igniter. Once the igniter has reached optimum pressure (100 to 200 milliseconds), the main pre-burner propellant valves are opened. After the pre-burner has lit and reached a consistent outlet temperature near 430 F (approximately 500K), the main torch igniter connected to the detonation channel is lit. After this igniter has reached optimum pressure, the main
hydrogen valve to the RDE fuel manifold is opened. This valve closes shortly thereafter leading to approximately 1 second of total burn time in the main detonation channel. A firing time of one second was selected to balance the need for data acquisition at steady-state operation with the desire to minimize thermal loads on the hardware.

To date, all tests have focused on total flow rates of approximately 0.45 lbm/sec (0.2 Kg/sec) and 0.9 lbm/sec (0.4 Kg/sec) at equivalence ratios between 0.4 and 1.6. Additional test series are planned at 1.35 lbm/sec and 1.8 lbm/sec with hydrogen before transitioning to methane as shown in Table 1. In general, the RDE ignites consistently and reliably at all conditions, and it is clear from high-speed camera footage that this ignition propagates at near CJ velocity around the annulus. The mean chamber pressure increases during these tests as expected and tends to consistently reach the target pressure value approximately 200 milliseconds after ignition. At this point the mean chamber pressure continues to climb slowly until shutdown. This behavior can be seen in Figure 3 for a typical test. The gradual increase in mean chamber during much of the remaining burn is likely due the increasing copper wall temperature. This increasing wall temperature reduces the energy deposited into the wall thereby reducing the cooling effect of the wall on the gas. It also leads to thermal expansion, and since the inner center-body heats up faster than the outer annulus due to the geometric profile, the total throat area contracts slightly during the burn.

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* Expected pressure value – test has not been completed yet.
** Thrust measurement is less accurate the low flow test case.

While mean chamber pressure tends to climb gradually during testing, thrust quickly climbs at ignition and settles at a mean value that tends to be approximately 80% to 85% of the theoretical maximum thrust predicted. Tests at the lower flow rate of 0.45 lbm/sec tend to produce smaller thrust value relative to the predicted maximum theoretical value, but the low flow rate and the large plumbing stiffness mean that these thrust values tend to be under-predicted somewhat.

While the mean chamber pressure and thrust observed during testing appear to be follow predictions fairly well, the high-speed footage, microphone data, and load cell data do not appear to show the expected resonant frequencies associated with detonation until right at shut-down. This can be seen in the spectrogram shown in Figure 4 for the same test as the data shown above. As before, this plot is typical of all tests to date. Data from the flush-mounted PCB microphone and ion probe are also suspect due to thermal overloading in the high heat-flux environment. While these results are still preliminary and more testing is scheduled in the near future, it appears likely that the primary behavior at this point is simply turbulent combustion. If detonations are occurring, it is likely they are only occurring near shutdown. Work is still ongoing on understanding this behavior.
Figure 4: Microphone spectrogram (left) and load cell spectrogram (right) data from a test at 0.9 lbm/sec and $\phi = 1.0$. The general behavior observed during this test is typical of all RDE tests to date except test 35.

6. Conclusions and Future Work

Purdue has designed and constructed an experimental RDE and pre-burner assembly at the Maurice Zucrow Laboratory complex for conducting high-pressure rotating detonation engine tests using liquid methane and liquid oxygen. Analysis prior to testing focused on overall mean fluid system performance and sizing, propellant mixing, transient injector response, and hardware thermal / structural analysis. Initial testing has focused on moderate pressure and low flow operation using gaseous hydrogen and liquid oxygen before transitioning to liquid methane. While ignition and combustion appear consistent in all tests to date, detonation behavior has not been consistently observed in the test article and only appears near shutdown. Testing is ongoing in an effort to better understand this.

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References


