Pulsed Detonation Rocket Engine Combustion

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1. Introduction

Traditionally, pulsed detonation engines offer the theoretical promise of increased performance through constant volume combustion processes; however, the tangible benefits have yet to be realized due to weight gains and hardware complexity often associated with modulating propellant injection. With renewed interest from NASA in exploring applications of detonation combustion in the rocket engine field,[1] the conducted research expands upon our initial findings for the development of a valveless pulsed detonation engine (PDE).

Originally motivated by the presence of pulsed combustion events in a hypergolic pintle injector engine,[2] the research first sought to reproduce the explosive events in an open chamber hypergolic engine with instrumentation to measure the pressure response. The first test series succeeded in reproducing violently pulsed combustion at the expense of instrumentation and hardware, as detailed in the AIAA Joint Populsion Conference proceedings, "*Valveless Detonation Concepts for Space Exploration*."[3] The second test series, detailed in these proceedings, progressed with modifications to instrumentation and hardware.

The present work faces similar challenges to traditional linear PDEs in that when liquid propellants are used, liquid phase atomization plays a critical role. The hypergolic propellants used include rocket grade hydrogen peroxide (RGHP) with an experimental fuel, fuel-a, consisting of Sodium Borohydride ($NaBH_4$) in an industrial solvent, triglyme.[4] The use of hypergolic fuels for detonation aims to eliminate the need for additional hardware to achieve deflagration to detonation transitions (DDT). Related research was conducted during Apollo-era hypergolic engine programs where "popping phenomena" were observed to disrupt engine operation.[5–7] While the Apollo-era research engines used nitrogen tetroxide and hydrazine derivatives, large magnitude pressure spikes likely associated with heterogeneous detonations were still observed. Initial theories suggest that the hydraulic feed system influences the frequency response of the pulsed combustion. It is our motivation to understand the link between the detonative phenomena seen with hypergolic fuels and expanding the behavior to pulsed detonation combustion.

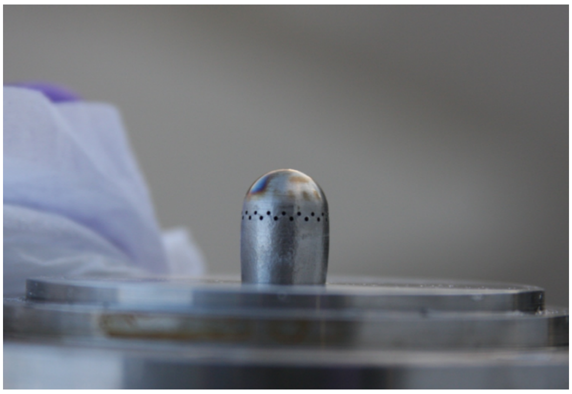
2. Experimental Modifications and Preliminary Results

Improvements to the test instrumentation included purchase of higher maximum pressure Kulites, high-frequency response piezo-resistive absolute pressure gages, installation of additional low-frequency Druck pressure transducers, and eventually installation of PCB piezo-electric dynamic pressure transducers.

At the end of the first test series (hot-fires 1-4) the pintle post showed structural failure, and as a result the second test series sought a redesign in material and hole sizing. The pintle post material was altered from 304 Stainless Steel (304 SS) to Hastelloy X starting with hot-fire 5. Furthermore, instead of using two distinct hole sizes, a uniform hole size was chosen for the pintle orifices based on manufacturing capabilities. Despite material and design changes, the Hastelloy X pintle showed signs of internal damage after hot-fire 6 where the pintle post bulged and expanded from a diameter of 0.384" to 0.410", as shown in figure 1. The figure shows different damage to the 304SS pintle after hot-fire 4. Consequently, hot-fires 7-10 proceeded with a spare Hastelloy X pintle injector.

While the pintle injector holes and the annular gap area were altered between the first test series (hot-fires 1-4) and the second test series (hot-fires 5-10), the upstream propellant feed-systems remained the same. Despite hardware failure between hot-fire 6 and 7, pressure data from chamber instrumentation showed interesting results. A pulsed frequency around 446 hz was present, similar to the 466 hz present in test series 1, throughout the system. That is to say that the pressure response was measured in the low-frequency chamber pressure transducers, high-frequency pressure transducers, and fuel and oxidizer manifold pressure transducers. Furthermore high-speed video from hot-fire 5 showed clear signs of super sonic flow exiting from the nozzle-less chamber.

(a) Damage to 304SS pintle after hot-fire 4



(b) Damage to Hastelloy X pintle after hot-fire 6

Figure 1: Pressure head losses from tank to manifold

Proceeding from the hardware failure of hot-fire 6, hot-fire 7 employed quick modifications to the chamber instrumentation. PCB piezo-electric pressure transducers were installed along with additional nitrogen purges for the low-frequency pressure transducers. The test data from the newly instrumented configuration produced a 431 hz tone across the instrumentation, and injector face transducers recorded peak pressures in excess of 6000 psi. It is worthy to note that hot-fire 1-7 used set tank pressures of 250 psi for the oxidizer and 200 psi for the fuel. In the high-frequency pressure time slice of the full test duration (0.750 sec) in figure 2, the peak pressures occurred in a quasi-periodic fashion once operation was no longer in the start-up transient. As mentioned initially, the research also aimed to measure feed system response to chamber pressure oscillations. From the hot-fires we notice that in general the fuel and oxidizer manifold respond at the same frequency as the chamber pressure. Due to the feed system set-up, the frequency response was often measured as far upstream as the fuel tank.

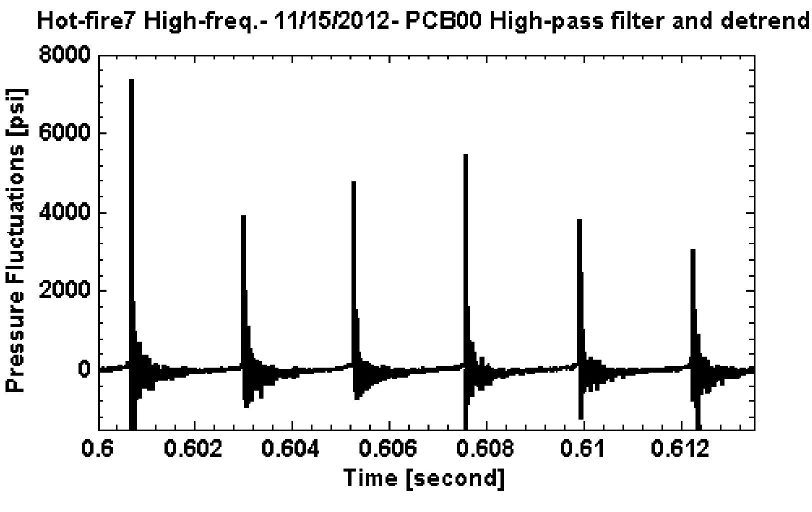
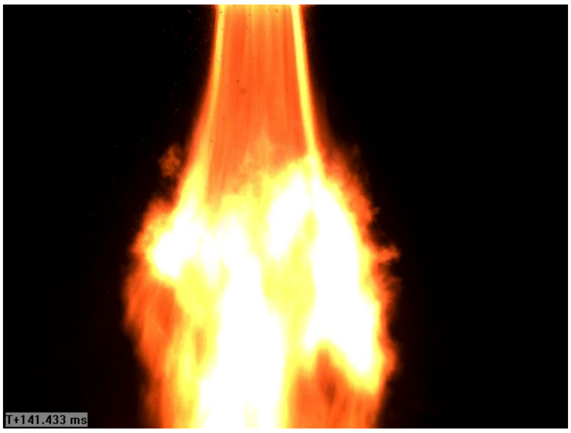


Figure 2: PCB 00 Filtered high-frequency pressure response for hot-fire 7

Proceeding with hot-fire 8 the test increased tank pressures by 20% overall, that is 300 psi for the oxidizer and 240 psi for the fuel. In this configuration the high-speed video showed that steady combustion was present for about 200 ms during start-up followed by a sharp transition into the pulsed behavior normally seen. During the steady combustion portion of the test, mach discs are present; the flow is furthermore highly unstable at times, contracting and expanding violently. The instabilities are visualized by the mach discs oscillating longitudinally. An example of these flow phenomena is seen in figure 3.

Much of the data collected remains to be analyzed. A main goal for the paper will be to explore the driving forces of the chosen frequency response of the system, the nature of the pulsed events, and the likely thermal choking present during the steady combustion events present in the latter hot-fire tests.



(a) Combustor exhaust without pulsation, steady in appearance

(b) Combustor exhaust without pulsation, unstable behavior with oscillating mach discs

Figure 3: Hot-fire 5 steady combustion during start-up transient with and without mach discs; chamber exit at top of frame

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