2022

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Recommended Citation

Rodriguez, Alexander G., "Thrust Augmentation of Rotating Detonation Rocket Engines" (2022). *Honors Undergraduate Theses*. 1194.
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THRUST AUGMENTATION OF ROTATING DETONATION ROCKET ENGINES

by

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A thesis submitted in partial fulfillment of the requirements
for the Honors in the Major Program in Aerospace Engineering
in the College of Engineering and Computer Science
and in the Burnett Honors College
at the University of Central Florida
Orlando, Florida

Spring Term, 2021

Thesis Chair: Kareem A. Ahmed, Ph.D.

Abstract

This thesis aims to perform a detailed analysis on a 5th Order Polynomial Nozzle, verifying its effectiveness in improving the thrust performance of a Rotating Detonation Rocket Engine. Rotating detonation engines are a promising engine type that uses detonations as a means of combustion rather than traditional conflagration. Through this method, these engines can produce significant amounts of energy while burning less fuel in the process. However, exhaust flow instabilities and swirl limit the engine's potential for use as a means of propulsion. The 5th Order Polynomial Nozzle was previously demonstrated to reduce and control this swirl; however, analysis was limited to side and back-end imaging. Using a recently built thrust stand, direct performance measurements were made with the nozzle being testing in several configurations. Discussed will be the data collected from the thrust stand, side-imaging to confirm flow behaviors similar to previous tests, and future work that is being done to analyze the exhaust flow.

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Nomenclature

RDE – Rotating Detonation Engine

RDRE – Rotating Detonation Rocket Engine

PDE – Pulse Detonation Engine

AFRL – Air Force Research Laboratory

PERL – Propulsion & Energy Research Lab

CATT Stand – Changeable Alignment Thrust Test Stand

Introduction

In recent years, there has been a growing interest in the use of pressure gain combustion as a means of propulsion. In the form of detonations, pressure gain combustion creates more energy than conventional combustion while consuming less fuel in the process. Additionally, many pressure gain systems are significantly less mechanically complex than their conventional counterparts. Despite difficulties with running reliably over extended periods, two types of pressure gain engines have been of particular interest: Pulse Detonation Engines (PDEs) and Rotating Detonating Engines (RDEs). [1] This report will focus on RDEs, efforts to improve their performance and flow stability, and verify the effectiveness of a 5th Order Polynomial Nozzle.

Unlike PDES, RDEs operate under a continuous detonation mode, further improving performance. This is achieved by creating detonation waves that circulate along an annular chamber, as seen in Figure 1. Many aspects of RDEs remain unknown despite extensive research, especially relating to their flow characteristics; however, some things have been discovered over recent years. One thing that has been found is that, depending on the engine's operating conditions, the number of detonation waves that can propagate can range from two to five. Additionally, because these waves rotate, it causes the exhaust flow to swirl, resulting in flow instabilities. As a result, the RDEs' effective thrust and efficiency are reduced as some of the exhaust flow moves laterally. In addition, it may create issues with properly choking the exhaust flow, limiting a convergent-divergent nozzle's effectiveness. As such, there is a need to mitigate these issues if RDEs are to replace constant pressure combustion for usage on rockets. [1]

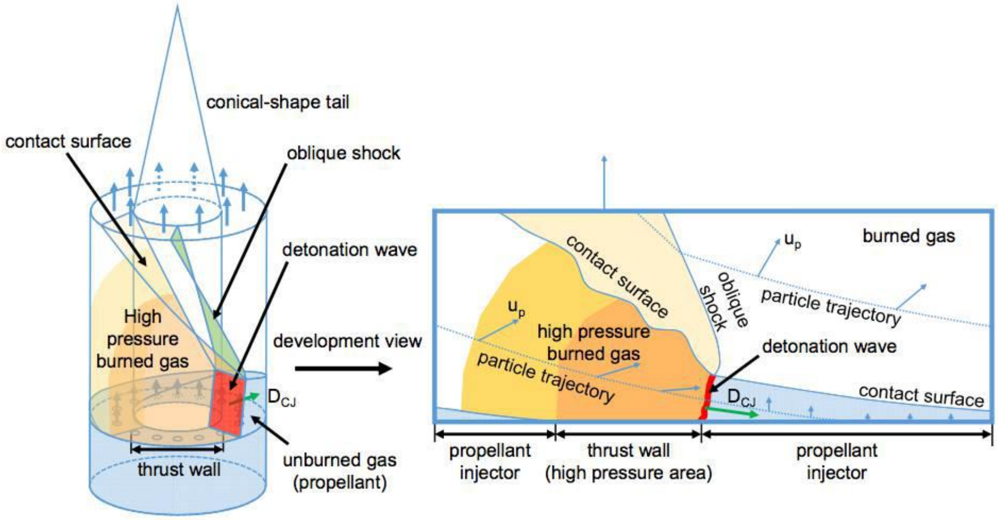

Figure 1: Detailed Flow Field of a Rotating Detonation Engine [2]

While The idea of detonations as combustion has been around since the 1800s, RDEs were only conceptualized in the late 1950s. In 1958, B. V. Voitsekhovskii successfully ran tests using carbon monoxide, ethylene, and hydrogen to produce detonations within a circular annulus. The detonations produced were found to rotate about the annulus, thus leading to the name of RDEs. In 1966, tests conducted in the United States successfully confined this process into a combustion chamber using a gas mixture of oxygen, hydrogen, and methane. While unsuccessful in sustaining the detonations after several cycles, these tests proved the viability of RDEs as a possible means of propulsion. Testing continued until the 1970s when there was a dramatic stop in RDE research due to issues with flow instabilities, high heat fluxes, and improvements in constant pressure combustion. [1, 3, 4]

The 2000s marked the resurgence of RDEs, with the head of this newfound interest being the Air Force Research Laboratory (AFRL). In partnership with various universities and private companies, significant progress has been made with implementing RDEs for power generation and propulsion, specifically for rockets (RDREs). While initial tests were done using airbreathing RDREs, tests done in 2016 by GHKN Engineering and Innovative Scientific Solutions found that using a gaseous methane-oxygen mixture produces a high impulse (up to 192 $\frac{lbf \cdot s}{lbm}$) [5]. As a result of this test, RDREs were proven to be viable for vacuum operations, and the fuel mixture used became commonplace for RDRE testing. Additionally, various other groups have looked into the nozzle design, detonation wave stability, various injector schemes and attempted to model the flow behavior within RDEs. [1]

The University of Central Florida (UCF), through the Propulsion & Energy Research Lab (PERL), has been one major group working on the development of pressure gain combustion. Collaborating with General Electric and AFRL, PERL has been developing airbreathing RDEs for energy generation and RDREs for rocket propulsion. As part of this effort, PERL has developed coal-burning RDEs, liquid H_2/O_2 RDREs, investigated exhaust flow stability, and in addition to a variety of other subjects of interest.

This thesis follows up on research done by Burke et al. at PERL. The objective of this research was to minimize the unwanted lateral velocities through the use of a 5th Order Polynomial Nozzle. The nozzle's design came about through Thwaites' Method for Boundary Layer analysis, which found that a curved nozzle design produced a smaller boundary layer than a linear design. Afterward, STAR-CCM+ was used to optimize the nozzle shape, culminating in a nozzle design with a L/H_{inlet} of 2.4 with a maximum pressure loss of 3.5%. [6, 7]

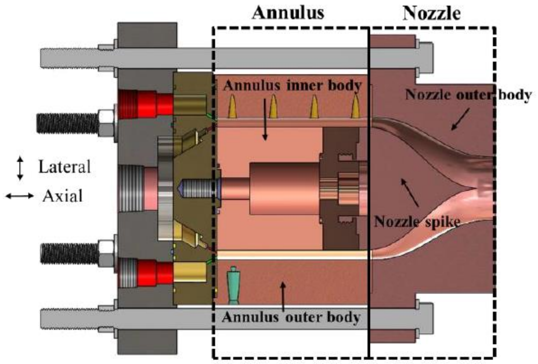

Figure 2: RDRE with the 5th Order Polynomial Nozzle [6]

To verify the effectiveness of the Nozzle, Burke et al. conducted a series of tests in which the RDRE was run under three nozzle configurations. The test configurations were: no nozzle, nozzle without an aerospike, and nozzle with an aerospike. Using a pair of high-speed cameras, they captured side and back-end imaging of the engine. These cameras ran at 150,000 FPS and had a 92 x 100 pixels resolution. Meanwhile, the engine used a gaseous mixture of methane (gCH_4) and oxygen (gO_2) with a mass flow rate of 0.6 lbm/s and a fuel-air equivalence ratio of 1.15 as the detonation wave speed, and the count had been well documented. Analyzing the data through PIVlab and MATLAB, it was found that the complete nozzle system reduced exhaust flow fluctuation magnitudes and spread. [6]

Research done by Fotia et al. provided a guideline for this thesis to follow. Unlike Burke et al., who focused on the effect of a nozzle on flow stability, Fotia et al. investigated the effects of choking the flow in addition to analyzing nozzles and their effect on thrust performance. The configurations tested consisted of a recessed and flushed bluff body and three types of conical aerospikes with different throat constrictions: unchoked, 20%, and 40% constrictions. Two key metrics used to measure the thrust performance were specific thrust F_{sp} (1) and specific impulse (2). [8]

$$F_{sp} = \frac{F_g}{\dot{m}_{air}} \tag{1}$$

$$I_{sp} = \frac{F_g}{\dot{m}_{fuel} \cdot g_0} = \frac{1}{g_0 \cdot TSFC} \tag{2}$$

Specific thrust was defined by the gross measured thrust F_g and air mass flow rate $\dot{m}_{air}$. Specific impulse was also defined by the gross measured thrust, but also the fuel mass flow rate $\dot{m}_{fuel}$, the gravitation constant g_0, and the Thrust Specific Fuel Consumption $TSFC. Thrust$ was measured using a horizontally mounted thrust stand with the nozzles tested on a 6 in. gaseous RDE. The RDE ran on a gaseous hydrogen and air mixture and ran through a series of mass flow rates from 0.36 to 1.70 kg/s alongside a range of equivalence ratios from 0.6 to 1.35. The results showed that the chocked aerospike configurations outperformed the other configurations in both specific thrust and impulse though the unchoked aerospike configuration occasionally matched or outperformed the chocked aerospike (though it was running at a mass flow rate of 1.14 kg/s while the chocked was at 0.76 kg/s).

Methodology

Modular Gaseous RDRE System

The modular rotating detonation rocket engine was selected for this series of tests. Based on a well-documented design by AFRL, this RDRE was chosen as it had been the testbed for previous investigations into nozzle design and exhaust flow stability at PERL. This would help verify the data collected and allow more accurate metrics for future testing with the same rig.

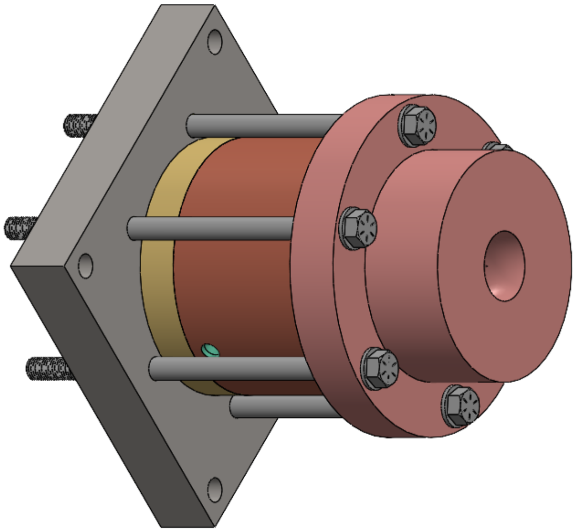

Figure 3: Modular RDRE Nozzle with Aerospike Configuration

The RDRE's annular chamber has an outer diameter of 3 in and a gap of 0.2 in. The inner body is recessed in into the RDRE by .277 in. The RDRE runs on a gaseous mixture, in this case, gCH_4 and gO_2. A mass flow rate of 0.4-0.8 lbm/s and a fuel-air equivalence ratio of 1.15 was chosen as the engine has been well documented under these conditions and was used in the previously mentioned tests by Burke et al. [6].

The 5th Order Polynomial Nozzle was selected for several key reasons. Outside of being readily available, data collected on it by Burke et al. was limited to exhaust flow analysis, and no direct performance metrics were recorded due to the lack of a thrust test stand. Additionally, during testing, the nozzle was found to be effective at controlling and compressing flow swirl, making it a foundation for research into exhaust flow stability at PERL. Because of its modular nature, four configurations were chosen for testing: no nozzle (baseline), nozzle with no aerospike, nozzle with aerospike (complete configuration), and aerospike with no nozzle. While the first three configurations had been tested, the configuration with just the aerospike had not. The reason for testing it now was due to interest after looking into past research, such as from the previously mentioned Fotia et al., in which such a configuration was tested.

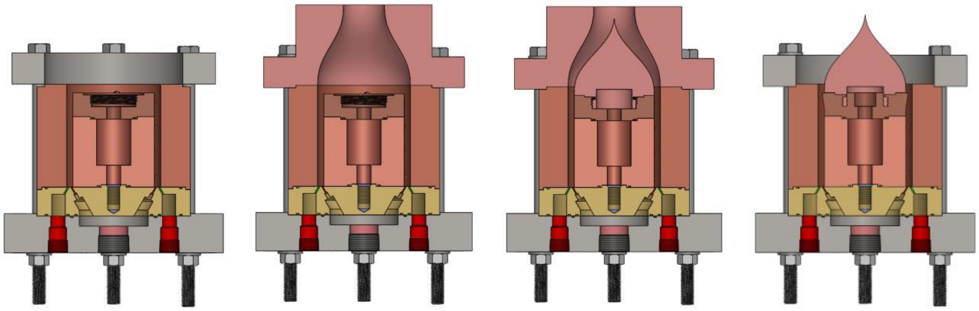

Figure 4: Tested RDRE configurations (from left-to-right): no nozzle (baseline), nozzle with no aerospike, nozzle with aerospike (full nozzle), and aerospike with no nozzle

Changeable Alignment Thrust Test (CATT) Stand

PERL began developing the CATT Stand towards the end of 2020. It is designed to operate at various orientations and significantly expands PERL's testing capabilities. While RDEs powered by gaseous fuels typically have no engine orientation issues, the engine must be mounted vertically when using liquid propellant. This simulates the actual operating conditions the propellant lines and pumps would experience. Another critical aspect of the stand is that it allows PERL to take direct thrust performance measurements. Previous tests were limited to calculating thrust and specific impulse based on the exit velocity of the exhaust flow in addition to the mass flow rate. The CATT Stand, by contrast, can take direct thrust measurements through the use of a built-in load cell. A series of known forces would be applied and measured to calibrate the stand, allowing for corrections to be made through the controlling software.

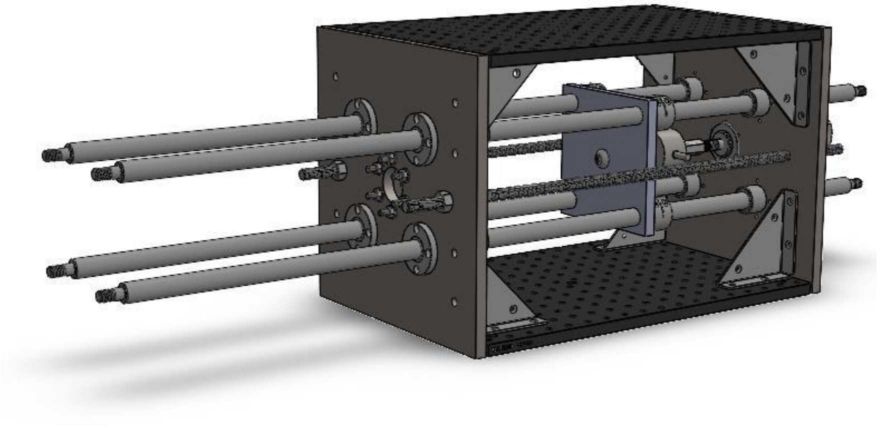

Figure 5: CAD of the CATT Stand

Regarding testing, the CATT Stand was orientated horizontally as they were done using a gaseous propellant mixture of gCH_4 and gO_2. Despite this orientation allowing for easy access and setup, complications arose while integrating it into PERL's current RDRE setup. This is because the stand's design is primarily built around a newer liquid engine instead of the lab's older gaseous RDRE. This necessitated changes to the propellant lines and the construction of a new RDRE backplate. The backplate was based on the original version, albeit with several notable changes. Before the CATT stand's creation, RDEs were mounted to a static test stand which could not record any data. As such, the backplate had to be extended out to accommodate CATT stand mounting holes. The additional weight required the corners to be filleted to reduce some weight and prevent it from damaging other laboratory surfaces.

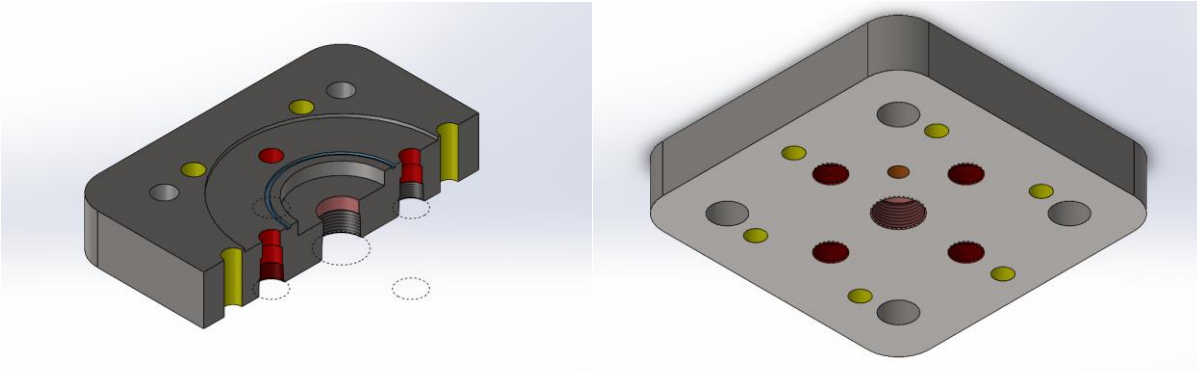

Figure 6: CATT stand compatible RDRE backplate.

CATT stand data was processed automatically through LabView. In addition to data collection and processing, LabView is responsible for operating all PERL's RDE testing rig, controlling propellant pumps, pre-detonation, and propellant flow, CATT stand operation and calibration, and high-speed camera timing. A Photron SA1.1 did Side-imaging at 45° with an image resolution of 128 x 128 pixels at 150,000 FPS. While LabView controlled the timing for this camera, the images it captured were processed through PIVlab, a MATLAB add-on.

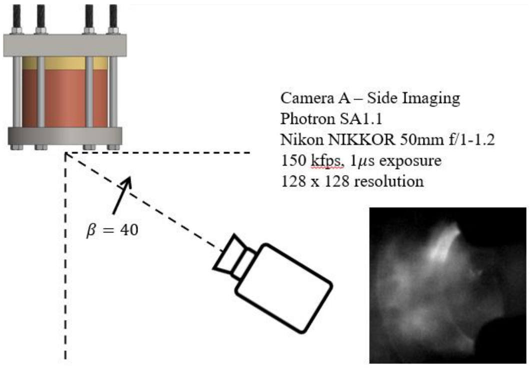

Figure 7: High-Speed Camera Orientation.

Results and Discussion

Eight tests were completed in total with the following amount of tests per configuration: two for no nozzle, three for the nozzle with no aerospike, two for the Nozzle with Aerospike, and one for just the aerospike. While a consistent amount of tests per configuration would have been preferable, testing was limited by a low fuel supply. The data below belongs to this first series of tests, with a second series being planned but never completed

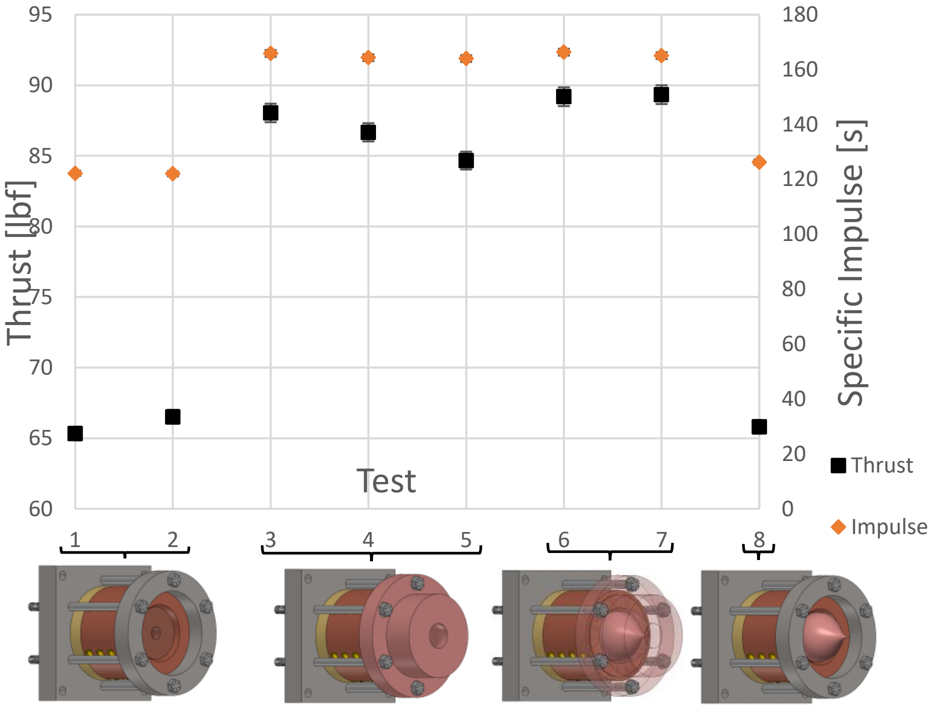

Figure 8: Total thrust and specific impulse for each test. 1-2: no nozzle, 3-5: nozzle with no aerospike, 6-7: nozzle with aerospike, 8: aerospike with no nozzle

Table 1

CONFIGURATION	Test	Thrust [lbf]	Impulse [s]	$\dot{m}$ [lbm/s]	ϕ
NO NOZZLE	1	65.32943	122.2192	0.534347	1.113134
	2	66.51945	122.0346	0.544899	1.088838
OUTER W/O AEROSPIKE	3	88.0363	165.8732	0.530563	1.116827
	4	86.66612	164.331	0.527213	1.131333
	5	84.66486	163.9938	0.516099	1.158745
FULL NOZZLE	6	89.18811	166.3289	0.536037	1.100304
	7	89.33466	165.0685	0.541015	1.085605
AEROSPIKE W/O OUTER	8	65.8086	126.2882	0.520922	1.136376

The CATT stand found that the outer body nozzle with the aerospike (full nozzle) was the most effective configuration with ~35% more thrust and a ~36% higher specific impulse over the no nozzle configuration. However, it was found to be only marginally better than the outer body nozzle with no aerospike configuration, which saw improvements of ~31% and ~35% to thrust and specific impulse, respectively. From this, it was determined that the most significant contributing factor to engine performance was the addition of the outer body nozzle. While the aerospike with no outer body nozzle did improve the specific impulse, with a ~3.4% increase, it had a negligible effect on thrust, with a ~0.2% decrease. While the second no-nozzle test produced greater thrust than the aerospike with no outer body nozzle, this may result from its higher mass flow rate. Due to the lack of data points, further testing is needed to verify the effectiveness of the aerospike with no outer body nozzle.

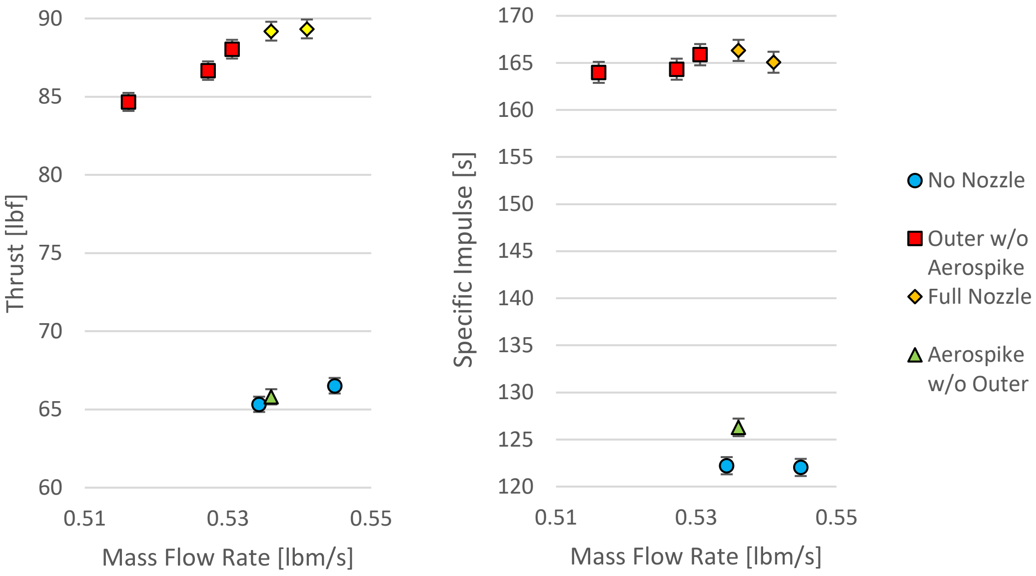

Figure 9: Thrust and Impulse Results for Test Series 1

A rudimentary method of flow analysis, based on a method done by Burke et al., was used with PIVlab tracking the movement of illuminated portions of the flow [6]. Despite efforts to make corrections to the data, the results of the side-imaging were found to be unreliable. It was found that the peak exhaust flow velocities ranged from ~53-464m/s, which is erroneous. For example, in the case of the no nozzle configuration, velocities were found to range from ~7-265m/s. This velocity range is well below that documented by Burke et al. for the same configuration, which was found to be 400-600m/s. The effective velocity of this configuration was calculated using the equation below to get a rough estimate of the theoretical exhaust velocity. It was found that the effective velocity of the no nozzle configuration was ~1199m/s, well above that documented by PIVlab

$$V_{eff} = I_{sp} * g = \frac{T}{\dot{m}} \tag{3}$$

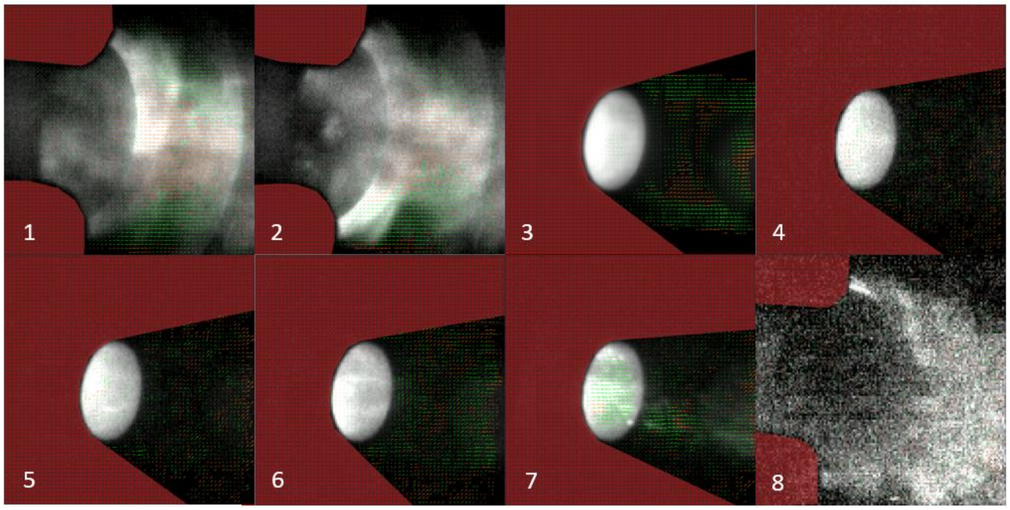

Figure 10: PIV mean flow velocities for each test. The masked areas are in red with green & orange velocity vectors. No Nozzle: 1 & 2, nozzle with no Aerospike: 3-5, Full Nozzle: 6 & 7, aerospike with no Nozzle: 8

Several issues may have led to this extensive range of peak exit velocities. As seen in tests 3-7, there is a lack of a distinguishable exhaust flow due to the presence of the outer body nozzle. As a result, PIVlab struggled to differentiate the flow from the background noise, with only occasional sparks of burnt copper giving the software anything meaningful to track. This issue was further compounded by the absence of PIV particles in the flow. Since the RDRE is not airbreathing, there was a lack of available compatible particle seeders. Current work is ongoing to address this issue for future testing. Another issue was likely the camera angle used. Unlike previous tests that set the camera at a side angle of 10-15 degrees, this series of tests used 40 degrees. While the velocities could be corrected in postprocessing, the camera angle meant that PIVlab focused on the engine itself instead of the exhaust flow resulting in these erroneous ranges of velocities.

Conclusion

After testing multiple nozzle configurations, the complete 5th Order Polynomial Nozzle was found to be the most effective nozzle configuration, increasing the thrust produced by ~35% and specific impulse by ~35%. While each nozzle component individually contributed to the improved engine performance, the outer body nozzle had the most significant impact, improving engine performance by 31% compared to a 0.7% improvement by the aerospike. In addition to verifying the work of Burke et al., future updates to the nozzle can use the collected data to judge their effectiveness.

Future Work

Alongside refinements on the nozzle, an effort is being made to improve flow diagnostic capabilities on the modular RDRE. Because current methods for flow analysis on the RDRE are relatively crude and unreliable, it has become necessary to develop a method of seeding the modular RDRE's exhaust flow. By seeding the flow, PIVlab would be able to perform single-pixel processing, allowing it to analyze the exhaust flow accurately.

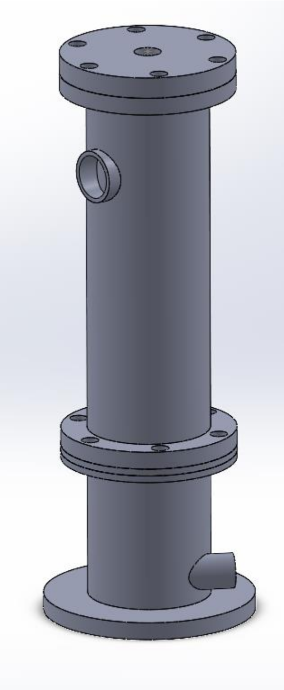

Figure 11: An early CAD of the methane particle seeder.

Particle seeders have been used to help analyze exhaust flow behaviors for other propulsion systems before; however, these systems have primarily been airbreathing engines. Because the modular RDRE does not run-on air, it was necessary to find an alternative method of seeding the engine. Methane was chosen as the seeded gas the oxidizer, gO_2, was deemed hazardous in the event of any reaction or combustion. For the seeding particles, large grain (~200 nm) Zirconium-Dioxide and Titanium-Dioxide were found to be prime candidates given that they are noncombustible, have a high reflective index, and have a high melting temperature [9]. Seeding the fuel may affect the engine's performance by diluting the methane concentration and clogging injector holes, among other issues. As such, the data collected in this thesis will help determine the impact on performance the seeder has before examining the flow.

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