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Designing and Fabricating a Vortex Aerospike Rocket Engine

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ABSTRACT

On average, 51% of a rocket engine's weight is in the cooling system, so finding an engine design that would drastically reduce the engine's weight, complexity, and production cost would be extremely beneficial. Small one-stage rockets will be the main method for smaller organizations to reach orbit shortly. The engine must be efficient at sea level and in space to achieve this. Since the start of spaceflight in the 1960s, many innovations on the typical rocket engine have been theorized, but few have been adopted. This project takes two innovations previously theorized and tested, vortex cooling and aerospike nozzle, and combines them in a proof of concept prototype. First, the prototype was designed in Computer-Aided-Design and then validated in a Compusonal-Fluid-Dynamic simulation. Next, the design was fabricated out of mostly hardware store materials. The custom nozzle design was made through lost-PLA-casting. Many tests were conducted with this prototype, and 4 data points were collected: nozzle temperature, combustion chamber temperature, chamber pressure, and thrust. The data collected showed the success of the vortex cooling method, as the chamber temperature was much cooler than the nozzle temperature. The engine's success as a whole was validated by the thrust data. This project shows that a vortex aerospike design is a viable and useful idea. A functioning rocket engine can be created relatively inexpensively and with widely available parts and proves that departing from typical rocket engine design can lead to beneficial findings.

Introduction

Definitions

- Vortex - a region in a fluid in which the flow revolves around an axis line, which may be straight or curved.
- Combustion - the chemical reaction between oxidizers and fuels that releases heat and gasses
- Combustion chamber - the part of the rocket engine that contains the combustion
- Fuel - one-half of the combustion equation; this will be propane gas in this project.
- Oxidizer - the second part of the combustion; this will be oxygen gas in this project
- Thrust - a force generated by the expansion of hot gasses
- Specific impulse (Isp) - a measure of how efficiently a reaction mass engine creates thrust
- Thrust-to-Weight ratio - the thrust of a rocket or rocket engine divided by its weight
- Active Cooling - a configuration in which some or all of the propellant is to cool the combustion chamber or nozzle to cool the engine

Background

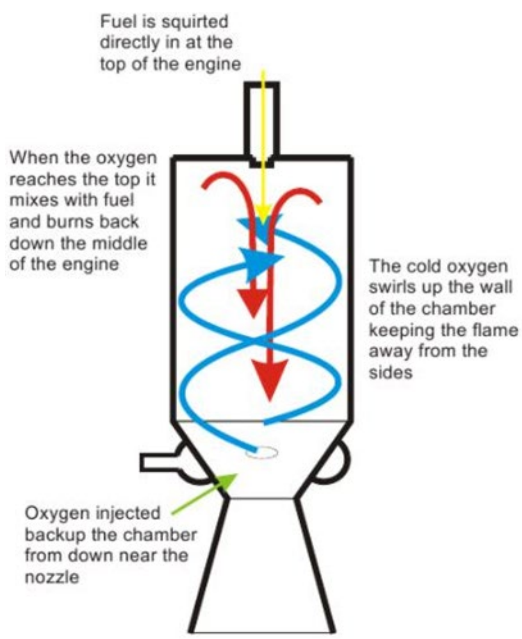
To fully understand how a vortex aerospike works, one must know how both a vortex engine and an aerospike nozzle operate and the advantages and pitfalls of both designs.

Vortex Engine Background

As the gasses of combustion are typically much hotter than the melting point of most metals, including high-performance aerospace metals, almost all industry-level rocket engines utilize some sort of active cooling to keep the combustion chamber and the nozzle from melting. The most commonly used method is channel cooling; this method is used on SpaceX's engines,

the Saturn V's F1 engines, and many others. In this technique, cryogenic liquid fuel or oxidizer is passed through channels machined in the combustion chamber walls and nozzle to wick the heat away. This method is extremely effective, but it is costly to fabricate and adds a lot of mass to the engine. On average, 51% of a rocket engine's weight is in the cooling system (Gaglani 2017). due to the necessary plumbing and extra materials.

This is where a vortex engine design is beneficial. Instead of injecting both the fuel and oxidizer together at the top of the combustion chamber- like most rocket engines -the vortex engine design injects the oxidizer at the bottom of the chamber, tangent and at a slight upward angle, allowing the cold fluid to vortex upwards, cooling the walls and protecting them from the hot combustion gasses in the center (see Figure 1).



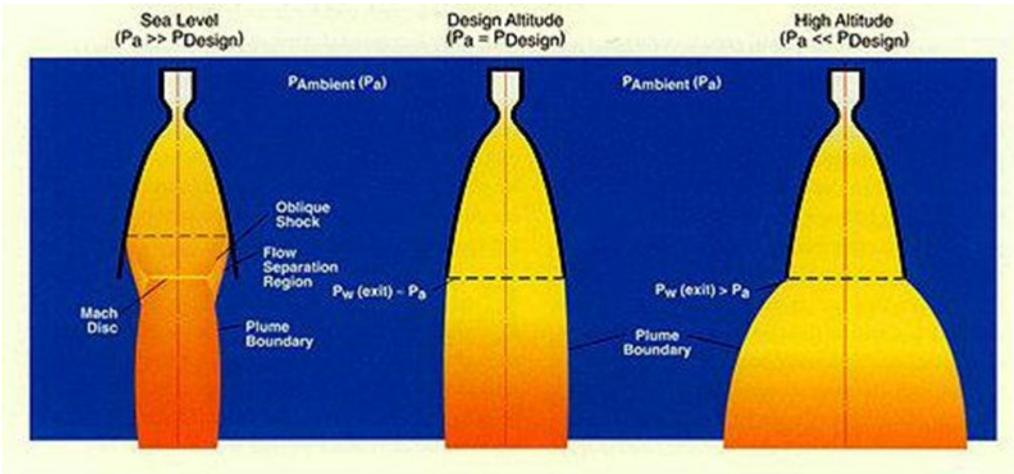
"Vortex Rocket Engine", (2008), Copyright 2008 Celestial Mechanics.

Figure 1. Diagram explaining how a vortex engine operates

This has the advantage of not needing to use cooling channels or extra plumbing, thus reducing weight, cost, and complexity. Vortex engines have been designed to work so effectively that some prototypes have kept the temperature at the wall so low that some could be built using plexiglass as chamber walls (Trinh et al., 2003). However, the drawback to this design is that cooling is still needed on the nozzle, and the angle at which the oxidizer is injected must be accurately designed. If the angle is off, the vortex rings could be too loose and let the hot gasses touch the wall or too tight, so the oxidizer will not reach the top of the chamber or stay in the vortex for too long and heat up.

Aerospike Nozzle Background

The most commonly used nozzle design in rocket engineering is called a de Laval or bell nozzle. This design looks like an hourglass when looked at from the side. This shape aims to take the gasses and accelerate them to a higher velocity while also keeping the gasses moving in a straight line (Figure 2).



Swathi et al

Figure 2. Diagram of de Laval nozzle at differing altitudes

This operation is where the biggest flaw of de Laval nozzles arises, as the length and diameter of the nozzle cannot be changed, and the nozzle is only perfectly efficient at one specific atmospheric pressure. This means at all other altitudes the nozzle is losing efficiency.

This is the reason most rockets have two or more stages: one for sea level and lower atmosphere and the other for the upper atmosphere and vacuum. This weakness is what the aerospike nozzle targets. Aerospikes use the atmospheric pressure instead of using the engine's geometry to constrain the gasses. The gasses are forced inward, follow the inner spike's contour and only expand as far outward as the atmosphere allows (Figure 3). This allows for almost perfect nozzle efficiency at all altitudes, even in a vacuum.

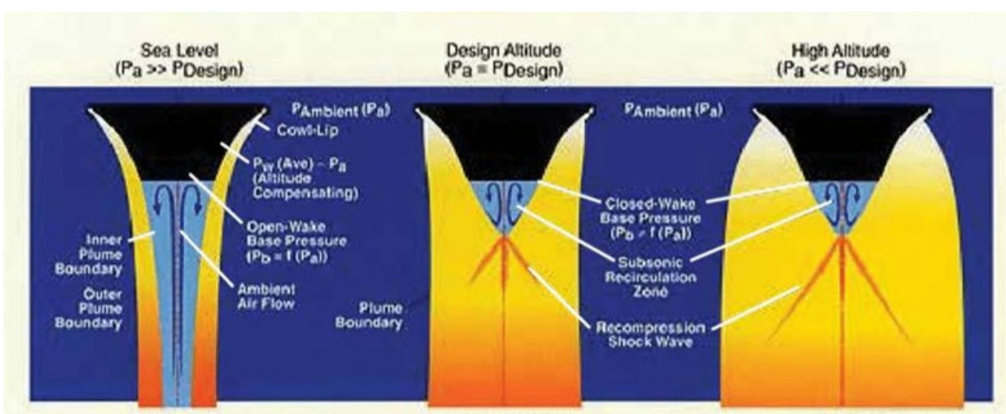


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Figure 3. Diagram of aerospike nozzle at differing altitudes

Literature Review

To design and fabricate a working and powerful vortex aerospike engine, it is important to break it down into its two defining features, a vortex engine, and an aerospike nozzle, and understand the years of research already conducted about them.

Vortex Engine Research

My research starts with a student paper exploring using rising air to generate power using a vortex. This paper has the best explanation for creating a vortex with static geometry. The student explains how the internal geometry of a tower was changed to generate a powerful vortex (Mustafa et al.)

The earliest research into vortex engines is a paper written in 1960 titled "Feasibility Study on Vortex Combustion". The study shows that vortex engines are possible and can produce a reasonable amount of thrust. This report was cited and used as the base for a 2003 Army Missle Comand paper exploring two methods of injecting the fuel and oxidizer (Trinh et al., 2003). Trinh et al. found that injecting the oxidizer tangentially to the chamber "does not require any traditional cooling methods, such as cooling wall channels wall and/or film cooling techniques", as this method "keep[s] a high-density fluid, and therefore, relatively cooler flows, in the near chamber wall" (2003). These findings were expanded upon by researchers at the Beijing University of Aeronautics and Astronautics, who aimed to find the best angle of fuel injection, the diameter of fuel injectors, and the angle of oxidizer injection (Li, Yu, & Lu, 2013).

A different type of study, different from the pure research type previously discussed, is one where a student designs, fabricates, and tests their own engine. They are all structured about the same way, with an introduction that establishes the issues that vortex engines could solve; a design portion where they cite papers like the ones previously mentioned to justify their design choices; a fabrication section where they go over the way they made their engine; and finally a testing segment where they validate the usefulness of their engine (Eldhose et al. 2017, Augousti et al. 2018, Numa 2015). These papers show that a student with limited resources can successfully design and build a working and powerful vortex engine.

Aerospike Nozzle Research

Aerospike research started in 1961 with a joint research paper between NASA and General Electric. This report is the first example of a physical aerospike being built and tested (Herman & Crimp, 1961). In the November 1961 issue of the ARS Journal, the author of a summarizing piece titled "Recent Developments in Rocket Nozzle Configurations" claimed that aerospike nozzle development could provide aerospace designers with a design that provides many benefits over classical nozzles (Rao). Herman and Crimp's research led to many developments in the seventies, eighties, and nineties, mostly focusing on using aerospikes for single stage to orbit (SSTO) applications (Rommel et al., 1995). This research culminated in a 1997 NASA paper titled "Multidisciplinary Approach to Aerospike Nozzle Design," which summarizes the research of the past 30 years and analyzes what is known about aerospikes through the lens of many different disciplines of aerospace engineering (Korte et al.).

Next, let us look at innovations in the typical aerospike nozzle design. One such innovation is described in a paper researching if thrust vectoring a toroidal aerospike can be achieved by injecting inert gasses into specific locations on the spike (Eilers et al., 2010). Another innovation in aerospike design is truncation. Truncation is when the end of the aerospike is cut off to reduce weight, but the efficiency loss is unequal because gas gets trapped where the spike would be and does the same function. Dakka and Dennison attempted to discover the best level of truncation for both efficiency and weight reduction through the use of CFD simulations (Dakka & Dennison, 2021).

Gap

My gap is clear; there has been plenty of research into vortex engines and over sixty years of aerospike research. However, there has never been a project or research into combining the two designs into one powerful engine.

Research Question

To what extent does an Aerospike Vortex design meet certain parameters to be an effective propulsion method for small-scale launchers? The parameters can be defined as:

1. The calculated price for a single unit at moderate production is less than $1000
2. Be made out of simple parts and materials
3. Have a thrust to weight ratio of greater than 30:1 at altitudes 0 km to 100km in 10 km increments
4. Have a specific impulse of 100 sec at 0 km of altitude and 120 sec at 100 km of altitude

Methodology

To successfully design and build a functioning vortex aerospike engine that meets or exceeds the stated goals, many studies and testing had to be completed. The process of this can be broken down into three distinct phases:

1) Design and Simulation
2) Prototype Construction and Testing
3) Final Design Testing
4) First I laid out my plan and presented it to the Institutional Review Board.

In the Design and Simulation portion, the goal was to design an engine that could be easily manufactured and meet the design goals. Then I used CFD simulations to validate the design and make necessary changes to create a theoretically perfect design.

In the Prototype Construction and Testing phase, I took the design made in the Design and Simulation phase and started to build it. Because the custom nozzle assembly needed to be metal 3d printed, it was by far the most expensive and irreversible part of the design, so I wanted to test the design of the nozzle in cheeper ways before committing to manufacturing the final part. I did this by iteratively testing designs made out of increasingly more expensive materials and closer to the final material, Inconel 625. This is also the phase where I built the test stand that took measurements of the engine.

In the Final Design Testing phase, I took the validated full design, I dialed in the fuel oxygen ratio and pressures, and started recording data.

I. Design and Simulation

The first step in the design process was designing what I would use as the combustion

chamber. I found a YouTube channel where this person built a fully functioning propane and oxygen rocket engine, and their combustion chamber was made out of a simple steel pipe. I liked this idea because it abided by my goal of making an inexpensive and simple engine, so I started looking for a 3-inch diameter steel pipe, and found this pipe (Figure 4). Along with this pipe, I also purchased a 3-inch diameter steel cap (Figure 5).

Figure. 4. 3” x 6” Black Iron Pipe

Figure 5. 3” Black Iron Cap

Next, I assembled the pipe in my CAD program, Fusion 360, to get a good scale of how it would look (Figure 6).

Figure 6. The pipe and cap assembled into the combustion chamber

Vortex Generators Design

Then I started designing the custom nozzle assembly based on the designs of Augousti et al. and Eldhose et al. First, I modeled the threads and the start of the vortex generating conduits (Figure 7). I continued to add to the design, implementing a high-temperature o-ring between the pipe and the nozzle assemble to reduce leaks, adding threaded holes for the quick connect fittings for oxygen, and a venturi-like geometry between the oxygen connectors and the combustion chamber to increase the velocity of the oxygen (Figure 8).

Figure 7. The nozzle assembly with vortex generators, fittings, and o-ring

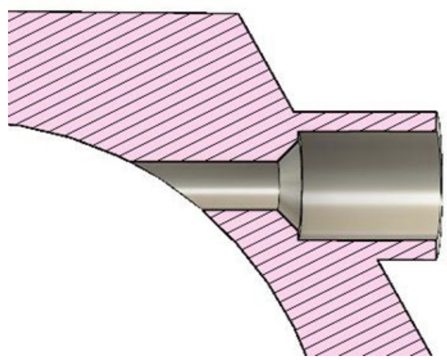

Figure 8. The oxygen inlet venturi

Next, I tested the vortex generators in the CFD program SimScale. To do this, I needed a negative of the design as the simulation needs the volume of the gasses to be simulated and not the walls (Figure 9). I set up the simulation at 101325 pascals or 1 atmosphere of pressure in the chamber to start, then the oxygen flow in at 500000 pascals or around 70 psi. The results from the simulation were so much better than I could have predicted. The vortex generators were doing exactly what they were designed to do: creating a long sustained vortex of oxygen from the base of the combustion chamber to the top (Figure 10 and 11). I then went on a testing campaign to change one thing on the CAD design and then test it in the simulation to see if it increased or decreased performance. Through this iterative testing method, I was able to dial in specific design variables before starting manufacturing.

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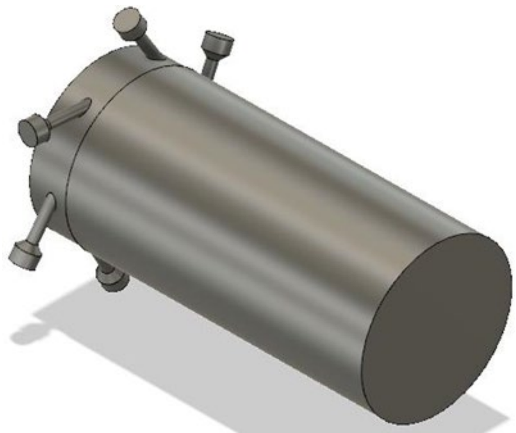

Figure 9. The negative of the combustion chamber

Figure 10. The CFD simulation of a single vortex generator

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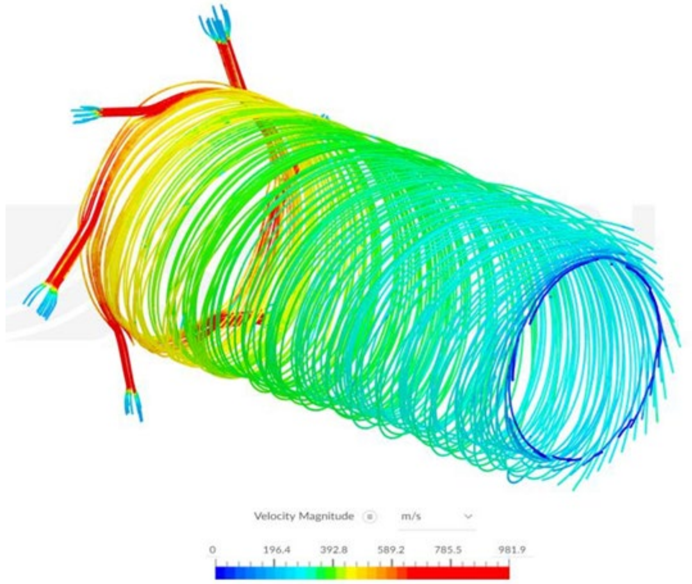

Figure 11. The CFD simulation of all six vortex generators

Plug Aerospike Design

The next part that needed to be designed was the aerospike portion of the nozzle assembly. Unlike typical aerospike nozzles that have the combustion chamber around the outside of the spike, my spike needed to take the hot gasses from the center of the combustion chamber and expand them to the outside: then, the spike is just like a traditional aerospike. This design is based on the research on plug aerospikes done by Johnson et al. The aerospike nozzle was also designed in Fusion360 (Figure 12).

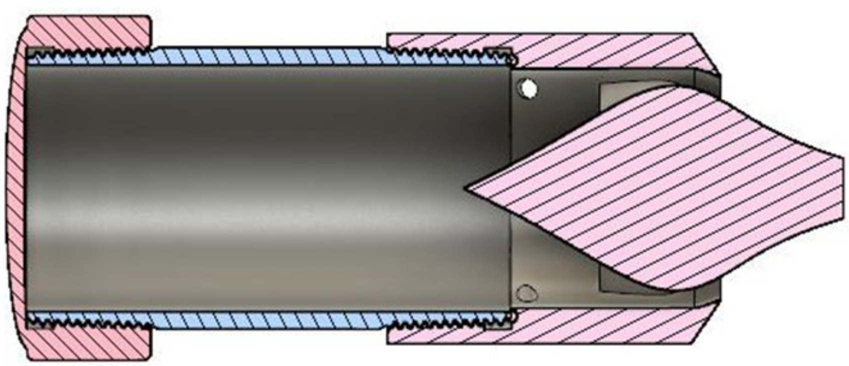

Figure 12. A side cut of the rocket engine with the plug aerospike

However, my plug aerospike design needed to be different from Johnson et al.'s design because, in their design, the plug is held up by a pillar going down the center of the combustion chamber (Figure 13).

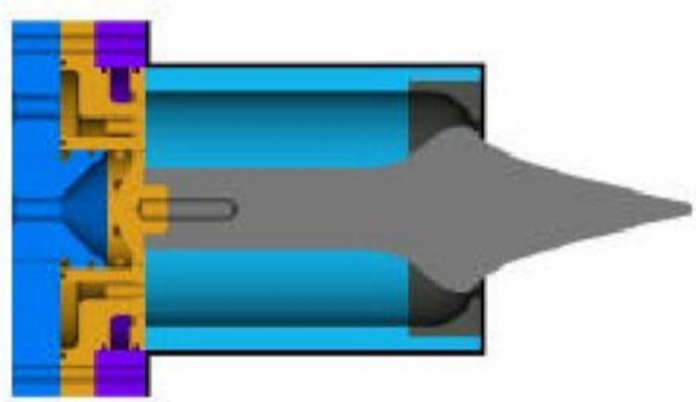

Figure 13. The type of plug aerospike detailed in Johnson et al's research

This design will not work with the vortex cooling method because the vortex keeps the combustion in the chamber's center. I came up with an alternate plug aerospike design; I call it a pylon design. In this design, the plug is held in place by six pylons from the outer shell (Figure 14). To ensure the pylons do not interfere with the flow of the gases, I shaped the pylons to be aerofoil shaped to reduce cross-sectional area (Figure 15).

Figure 14. A back view of the nozzle to see the six pylons

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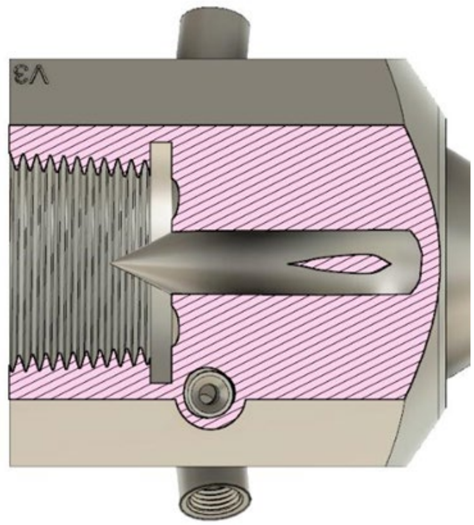

Figure 15. A cutaway view of the size of the nozzle to see the airfoil shape

Once the initial design was complete, I started testing all of the aerospike features in CFD. First, I tested if the geometry of the spike itself was correct and that the truncation would work correctly (Figure 16). There were various iterations of the aerospike geometry to find an optimal shape.

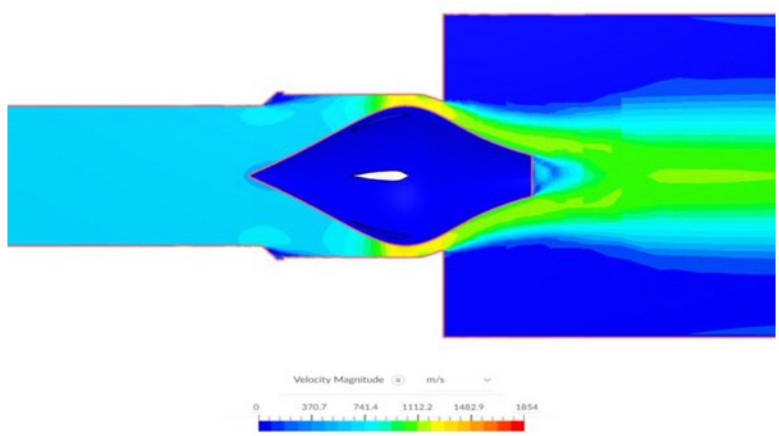

Figure 16. Sideview of the optimal aerospike at 1 atm of pressure

As seen in the simulation, the plug aerospike takes the slower moving gases and compresses and accelerates the gas to the convergent zone and then outward in the divergent zone. Also, just like Dakka & Dennison's research, a truncation of 40% is the best balance between weight reduction and efficiency loss. Also, the captured gas providing the same function as the truncated spike can be clearly seen. Next, I needed to validate my idea that the aerofoil-shaped pylons would not interfere with the flow of gases, so I tested it in the CFD simulation (Figure 17).

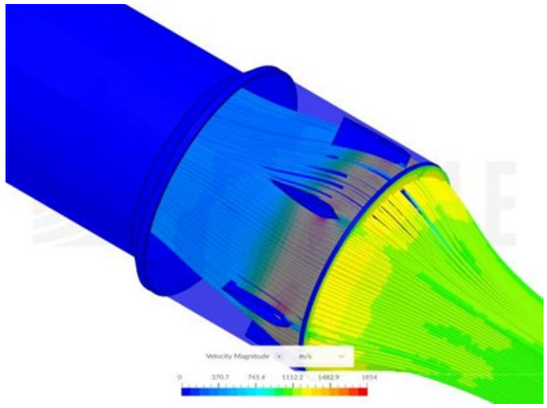

Figure 17. CFD simulation of the flow around the pylons

Fuel Injector Design

Once the aerospike design was completely validated in CFD simulations, I started working on the fuel injector. I wanted to use parts from the local hardware store to continue my goal of using easily accessible parts. I started the design with a ¼" quick connect fitting (Figure but was worried that the fuel would not get properly dispersed along the top of the combustion chamber. So I came up with the idea to machine a brass part to go on the end of the quick connect fitting to help spread the fuel (Figure 19).

Figure 18. ¼" quick connect fitting

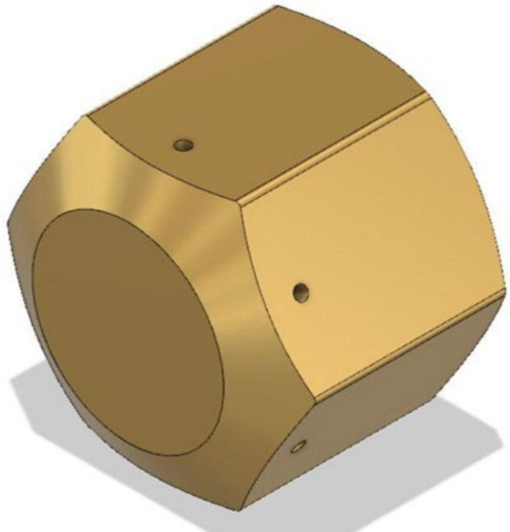

Figure 19. Brass dispersal cap

I 3D modeled the injector, I tested it in a CFD simulation to fine-tune the pressure to inject the fuel into the combustion chamber (Figure 20).

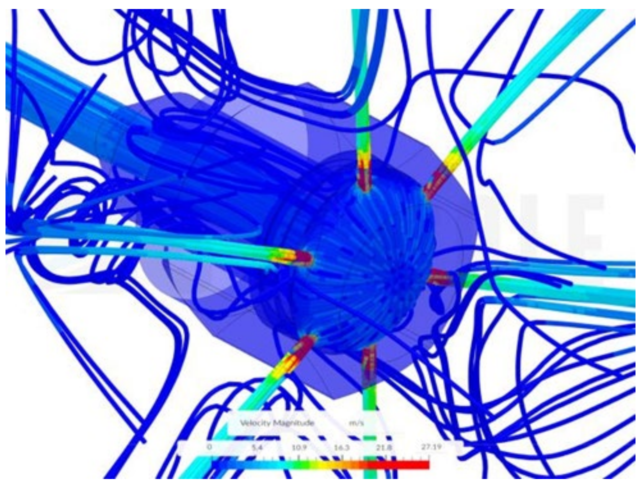

Figure 20. Simulation of optimal pressure for fuel injection

II. Prototype Construction and Testing

After the entire design had been validated in simulations, I started the second phase of fabricating the prototype and test stand and performing the preliminary testing.

To make sure there was no waste of time or money, I laid out 3 step plan to ensure that every level of the prototype was functioning properly before moving on to a more expensive manufacturing process. Step 1 was 3d printing the nozzle and testing it with compressed air and smoke to make sure that the vortex was forming properly. (Figure 21).

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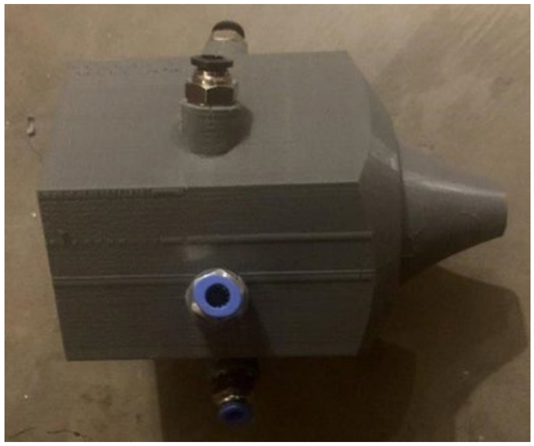

Figure 21. The 3d printed nozzle

Step 2 was manufacturing the nozzle in aluminum. The method I chose is called last-PLA-casting. This method starts with 3d printing the model desired in extremely thin plastic. Next, the model is submerged in the Plater of Paris and left alone to cure. Then the new mold is baked at around 500-600c to set the mold and melt out the plastic model. Finally, molten aluminum is poured into the mold and left to cool. I performed this entire process and was semi-successful; the nozzle came out with some of the geometry needed but not all (Figure 22).

Figure 22. This is the nozzle I cast out of aluminum

With the nozzle manufactured to a quality high enough to start testing, I started designing and constructing the testing apparatus. The method I used to measure thrust is a 2x4 lever with the engine on the left side facing upward, so it thrusts downward; the force pulling upward on the right side can be measured and is proportional to the thrust of the engine (Figure 23).

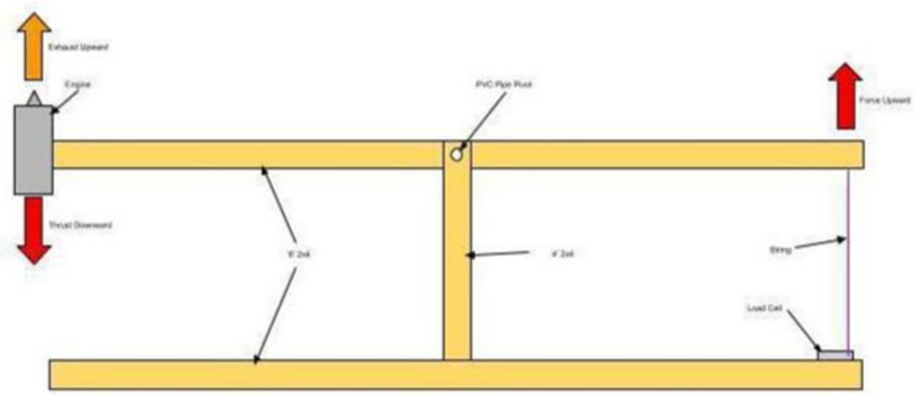

Figure 23. Diagram of the testing apparatus

I chose this design for my testing apparatus because it provides many benefits and safety features. It keeps the exhaust upwards to not damage concrete under the test stand. Also, all of the electronics and measurement devices can be on the opposite side from the engine, protecting them in case of a RUD (Rapid Unscheduled Disassembly). Another safety feature is that if the engine's mounts fail, the engine will just slam into the ground and not fly in an unknown direction.

The next part of the testing apparatus was the electronics system. I first designed the circuit I would need in a circuit diagraming software (Figure 24).

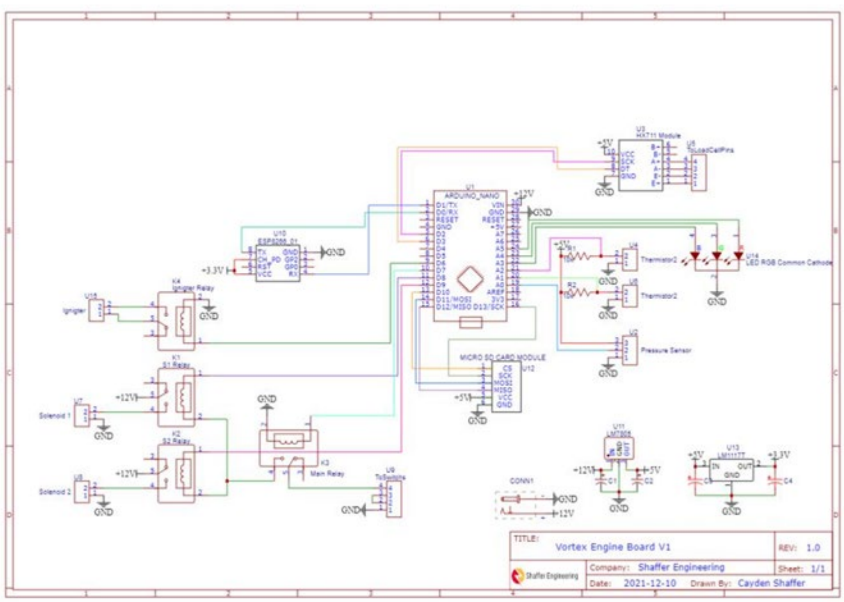

Figure 24. The circuit diagram

The inputs of the circuit were two temperature sensors, a pressure sensor, and a load cell that measured thrust. All of this data was sent to the core. The core of the circuit was an Arduino Nano microcontroller. The Nano took in the sensor input, saved it to an SD card, sent it to an ESP8266 chip, and ran safety checks. I chose the Nano as it is a small and powerful chip with plenty of I/O (input and output) pins. The ESP8266 chip took the sensor data from the Nano, hosted a website that displayed the data and took in control inputs sent back to the Nano (Figure 25).

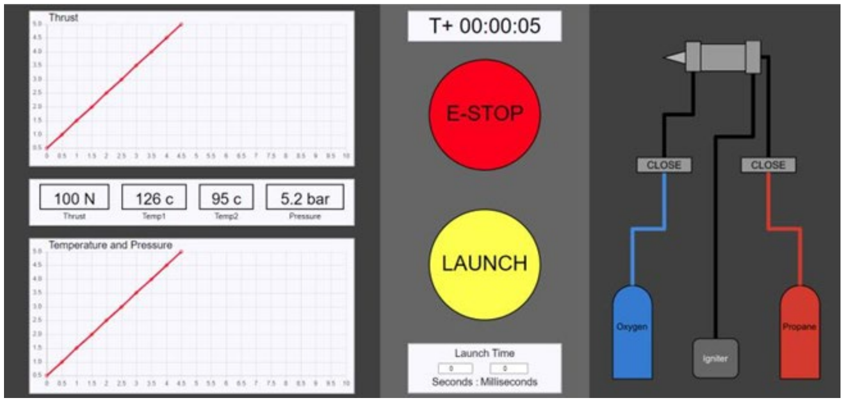

Figure 25. Control Website

The left side of the control website displayed the sensor data in both graph and number form. The center had the emergency stop, launch, and T+ timer. On the right side, individual valves could be controlled.

First, I prototyped the circuit design, and when that worked, I designed and ordered and custom PCB (Printed Circuit Board) to more easily assemble and move the circuit (Figure 26).

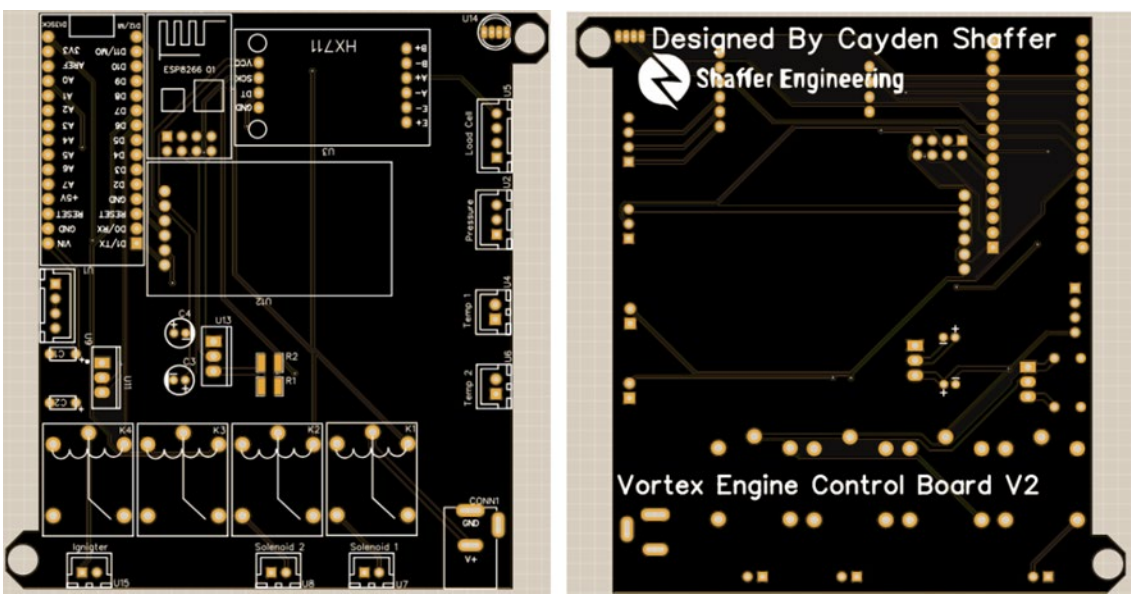

Figure 26. PCB Design

III. Final Design Testing

Once everything had been designed and built, I started testing. I set the whole apparatus up in the testing location and started testing (Figure 27).

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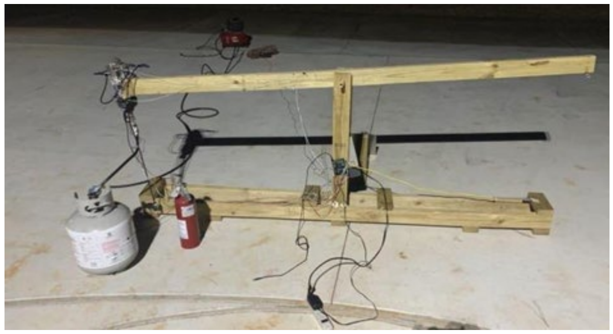

Figure 27. Testing Picture

To test, I first did many smaller tests to find the correct pressure to inject the fuel and oxidizer; then did longer multi-minute long tests to collect data. I was able to complete three full tests (Figure 27,28,29).

Figure 27. Picture of First Test

Figure 28. Picture of Second Test

Figure 29. Picture of Third Test

Findings/Analysis

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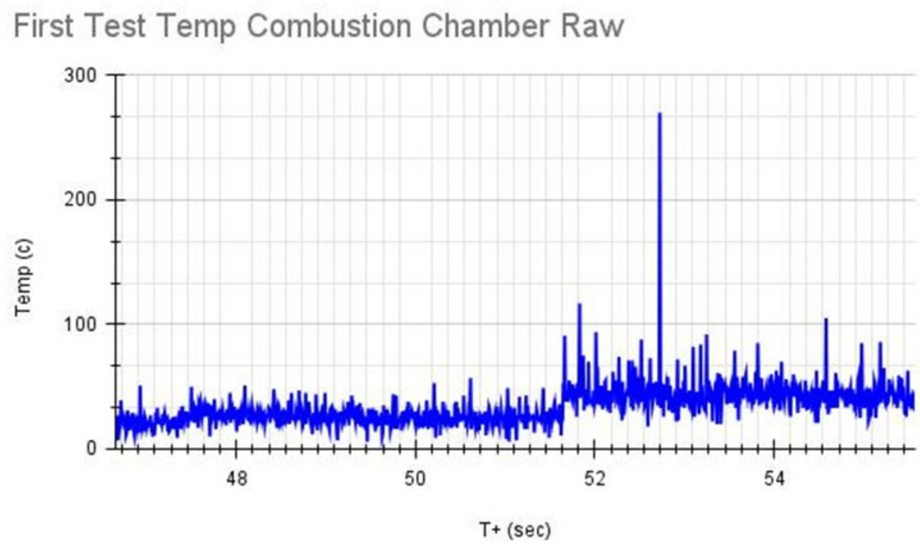
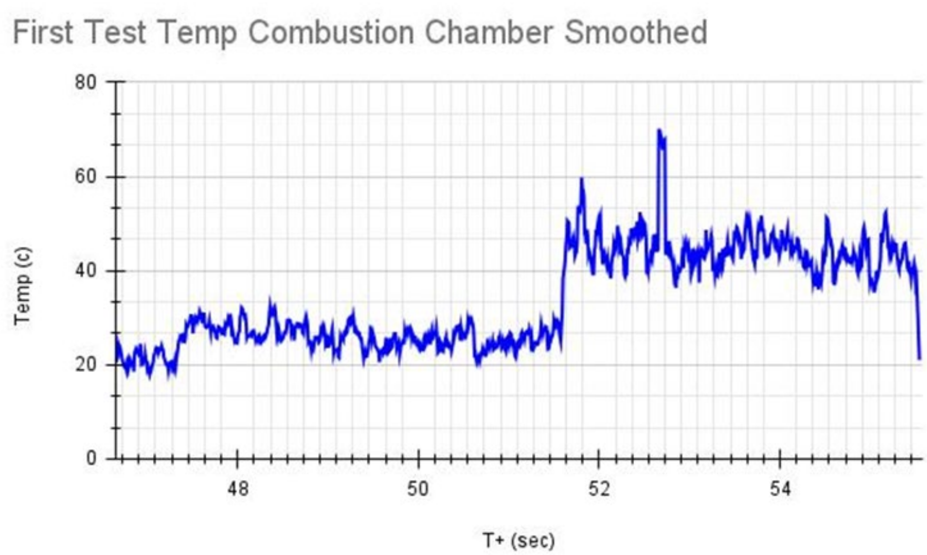
Temperature Findings

Only the combustion chamber temperature probe was operating during the engine's first test. Also, the raw data out of the probe was noisy and had variations, so I ran it through a running average to smooth the data out. This smoothing algorithm was used on all of the following data to remove noise.

First Test Temperature Combustion Chamber Raw

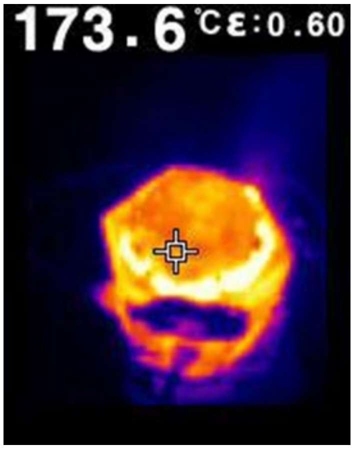


First Test Temperature Combustion Chamber Smoothed



Even with this averaging, the temperature is still quite noisy. However, an overall trend can be seen. About halfway through the burn, the temperature jumped from around 20℃ to around 50℃, where it stayed constant for the rest of the burn.

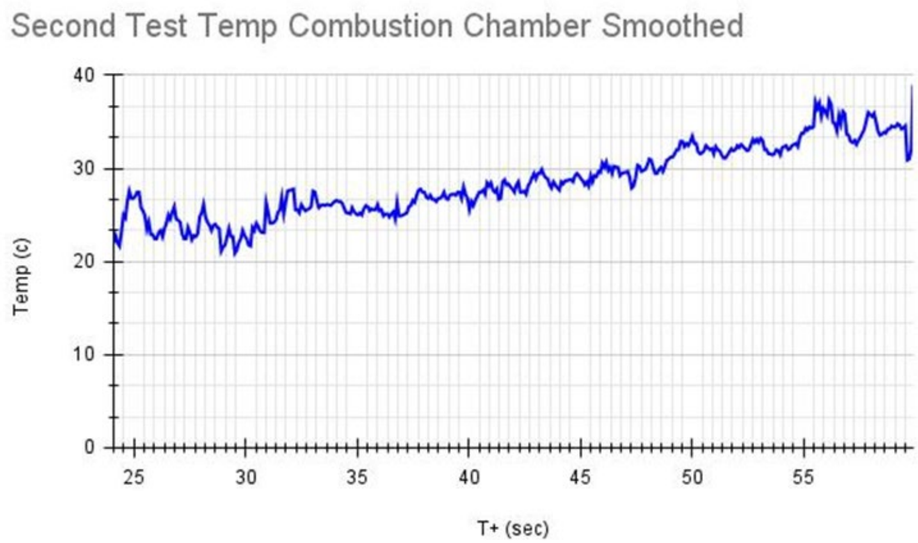
First Test Thermal Camera Nozzle



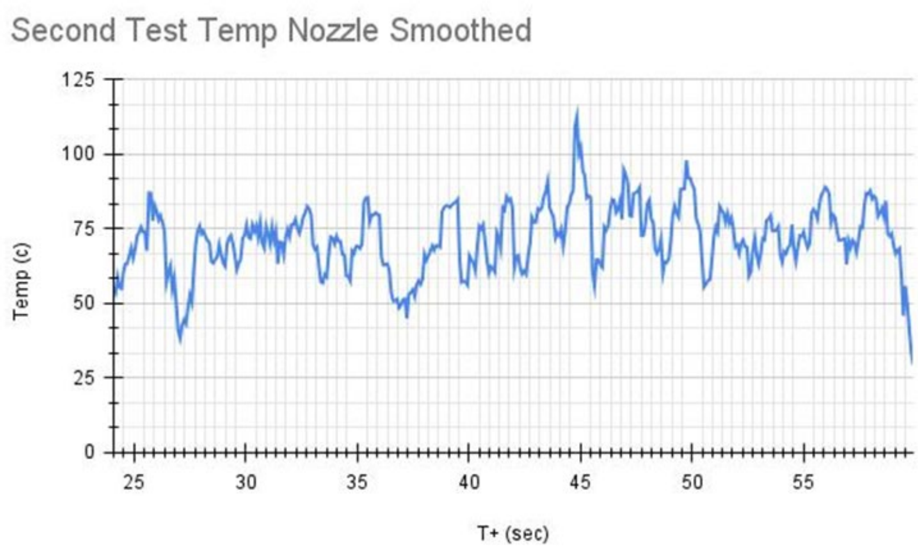
First Test Thermal Camera Combustion Chamber

In these photos taken by a FLIR thermal imaging camera, one can see the difference in the temperatures between the combustion chamber and the nozzle.

Second Test Temperature Combustion Chamber Smoothed

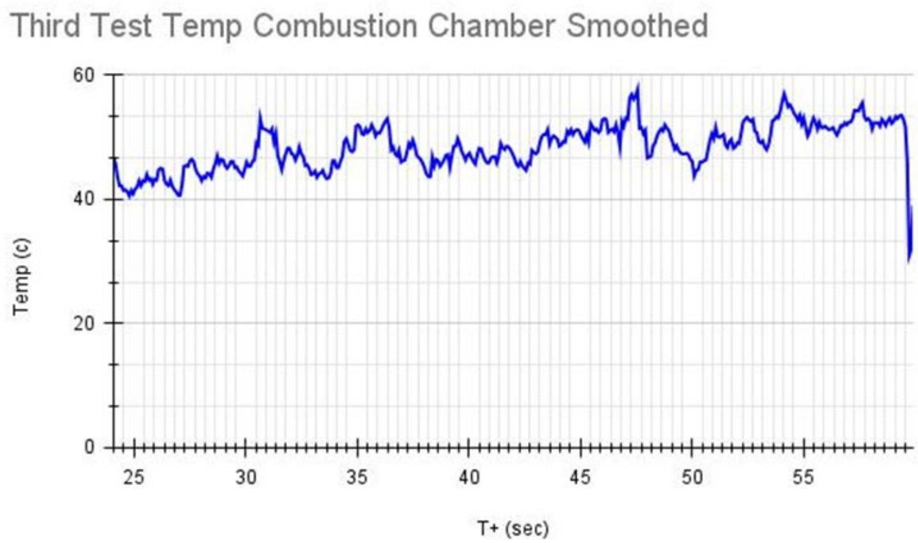


Second Test Temperature Nozzle Smoothed

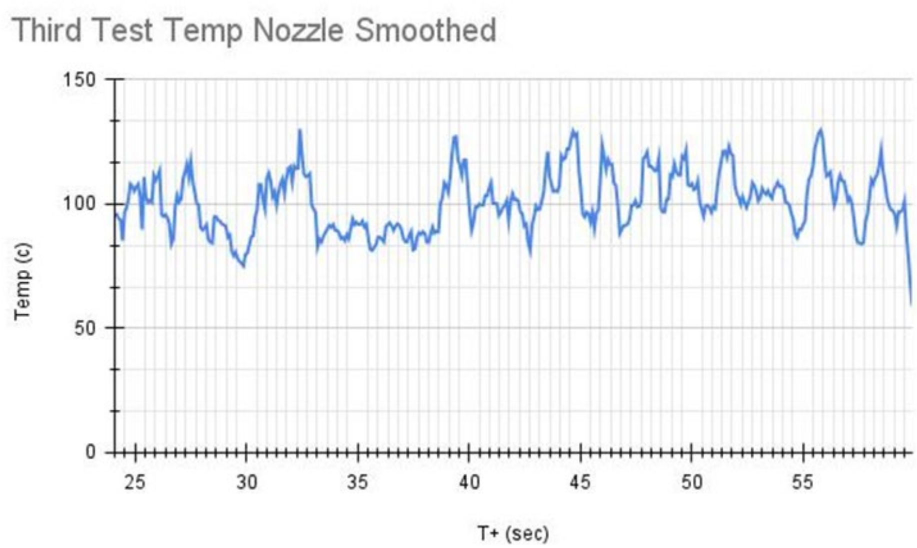


In this test, both temperature sensors were recorded and were relatively consistent. The combustion chamber temperature started at 23℃ and rose at an average of 2.53℃/s (with an r-value of 0.938) to around 35℃. In contrast, the nozzle temperature started at 55℃ and stayed pretty constant with an average growth of 0.212℃/s (with an r-value of 0.234).

Third Test Temperature Combustion Chamber Smoothed



Third Test Temperature Nozzle Smoothed



Like the previous two tests, the same common trend of the nozzle temperature being much higher than the combustion temperature can be seen. Because this test was taken only a few moments after the second test, both temperatures started higher than the previous two tests, but the overall trend is similar.

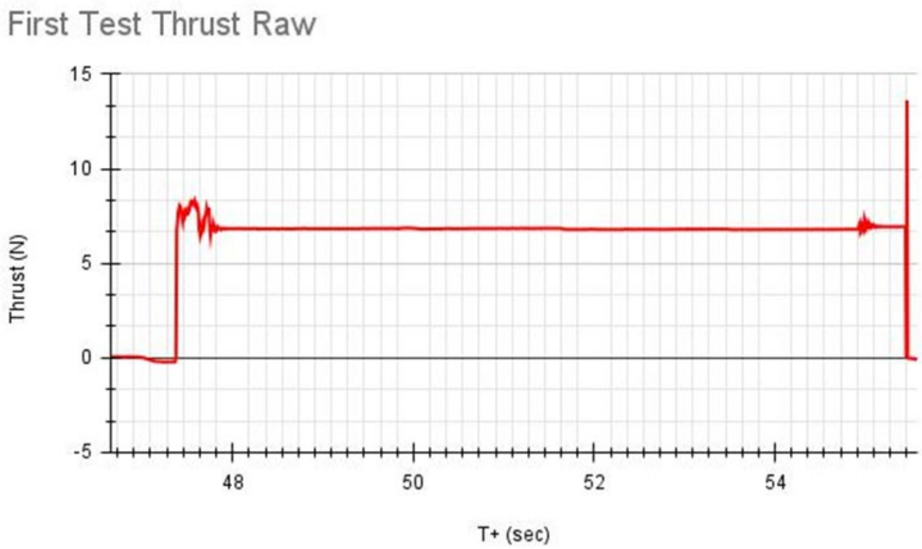
Temperature Analysis

All of the temperature data collected shows the combustion chamber temperature was much lower than the temperature at the nozzle. This is important because the nozzle is not cooled through any method, so it is a control for an uncooled surface. In contrast, the combustion chamber is the portion where the vortex is, and it protects the walls. The large disparity in the two temperatures proves the effectiveness of the vortex cooling method and my implementation of it. This helps fill my gap as it proves the validity and success of the vortex cooling method in combination with an aerospike. This shows that a fully functioning vortex engine that does not need any exotic materials or metals can be designed and fabricated for extremely low costs.

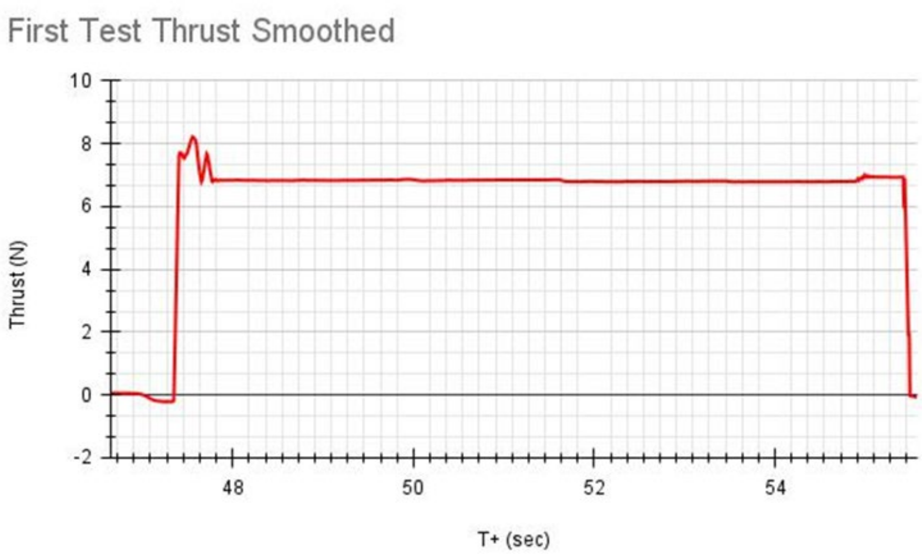
Thrust Findings

The thrust data came in as the weight in grams on the force sensor; I first had to change the grams to newtons. Next, I ran the thrust data through the same smoothing algorithm.

First Test Thrust Raw

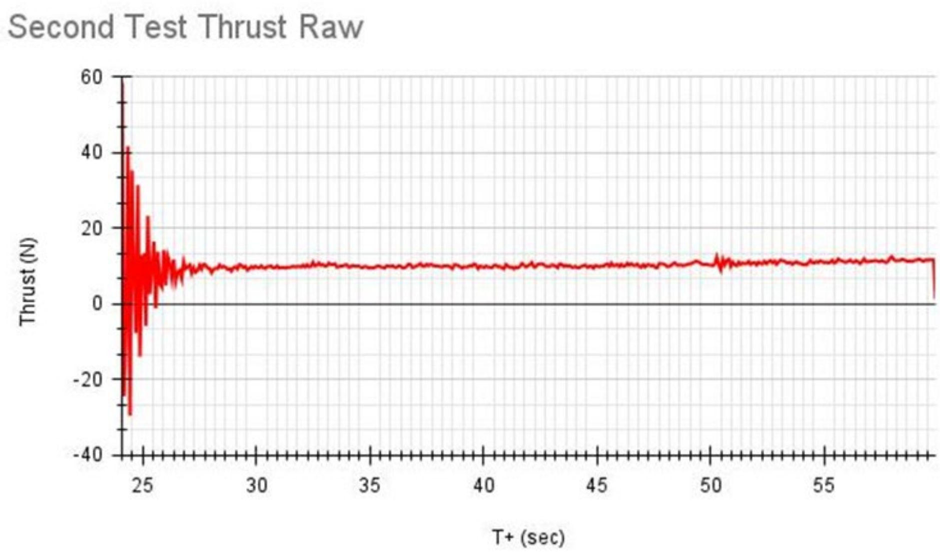


First Test Thrust Smoothed

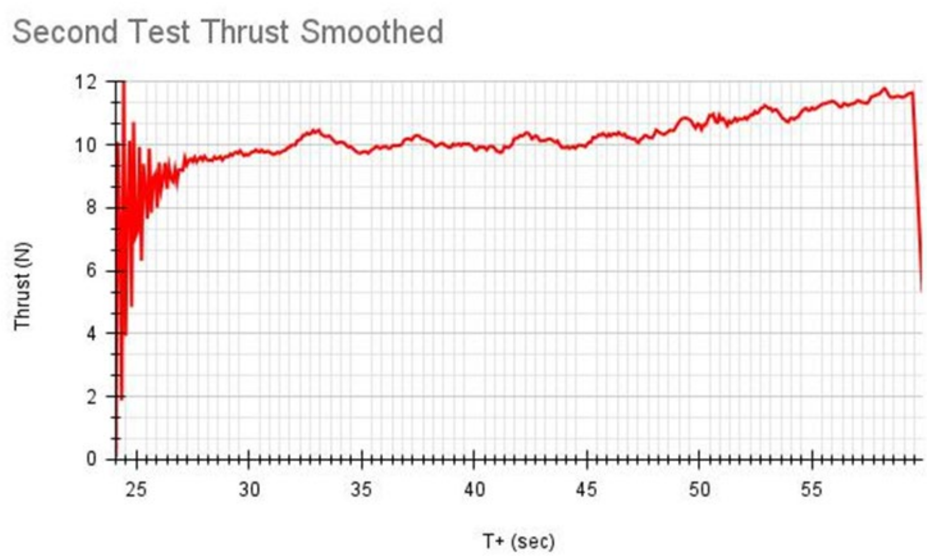


The thrust curve can be clearly seen in both the smoothed and the raw thrust data. With a spike at the start, the thrust over the next 8 seconds is extremely consistent, with an average of around 7 newtons of thrust.

Second Test Thrust Raw

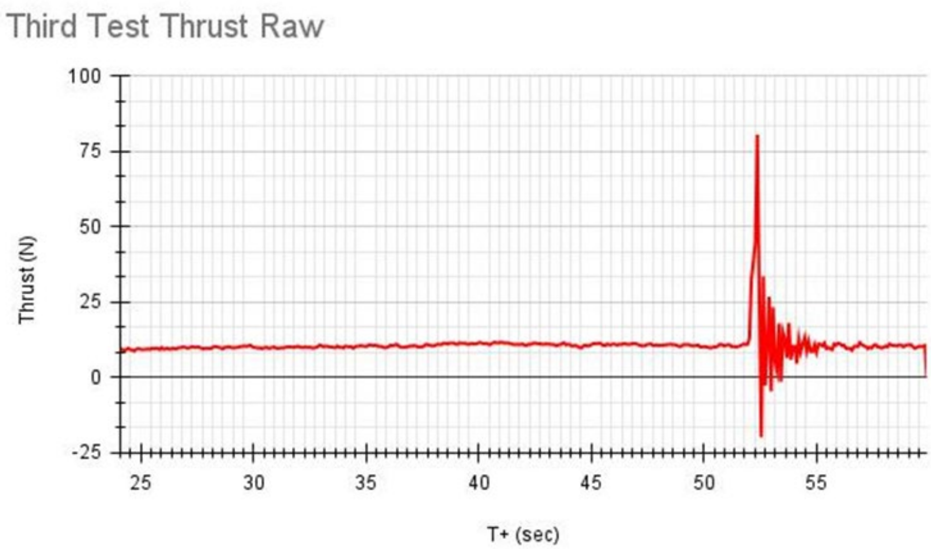


Second Test Thrust Smoothed

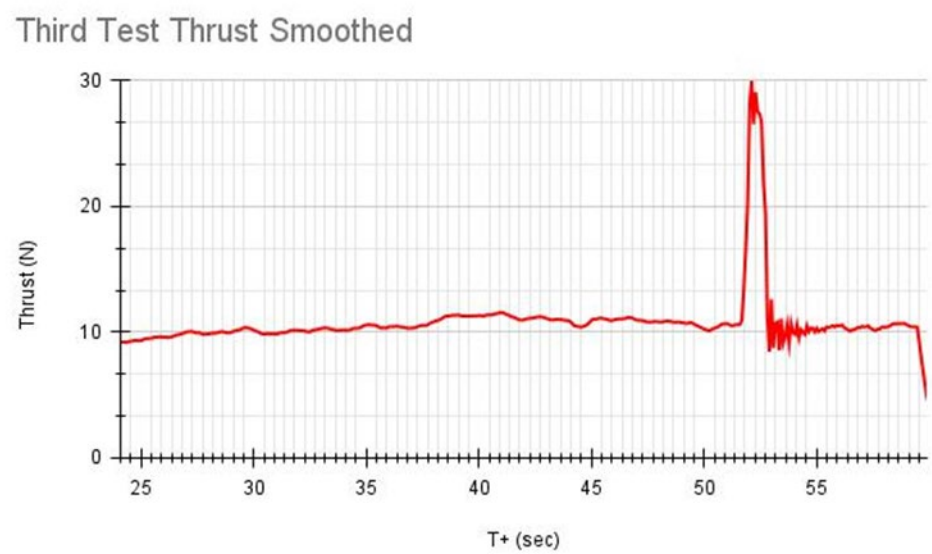


The stand slightly oscillated initially during this test, then settled to a steady rise in thrust over the 30-second test. The thrust started at around 9 newtons and ended at around 12 newtons with an average of around 10.5 newtons.

Third Test Thrust Raw



Third Test Thrust Smoothed



This test started very well with a constant 10 newtons of force until around T+ 50 seconds, when there seemed to have been an anomaly. After the spike caused by the anomaly, the thrust returned to around 10 newtons for the rest of the burn.

Thrust Analysis

I ran 80 seconds of burn time in the three test trials I ran. The thrust produced in all tests was extremely consistent at around 10 Newtons of thrust. This achieves my goal of designing and fabricating a working vortex aerospike engine and proves that this design can be fabricated at a low cost. This fills the gap I identified at the beginning of this paper: the lack of research on a combined aerospike and vortex engine.

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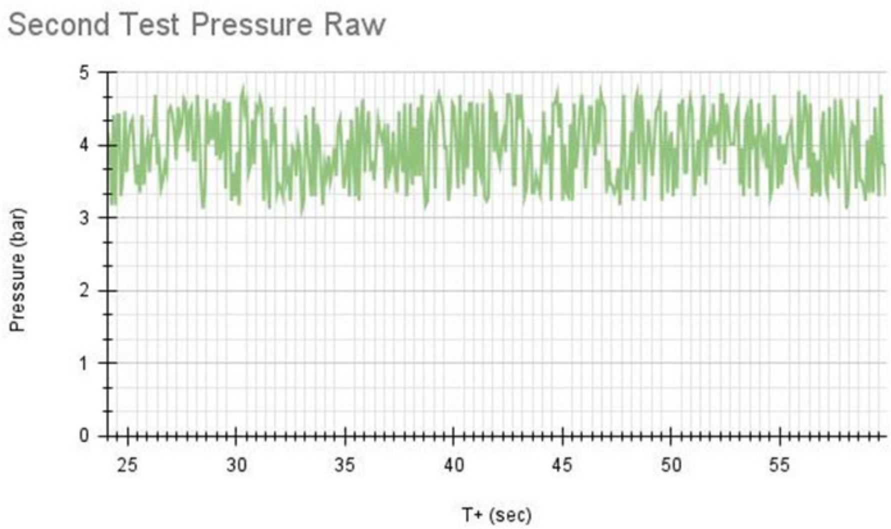
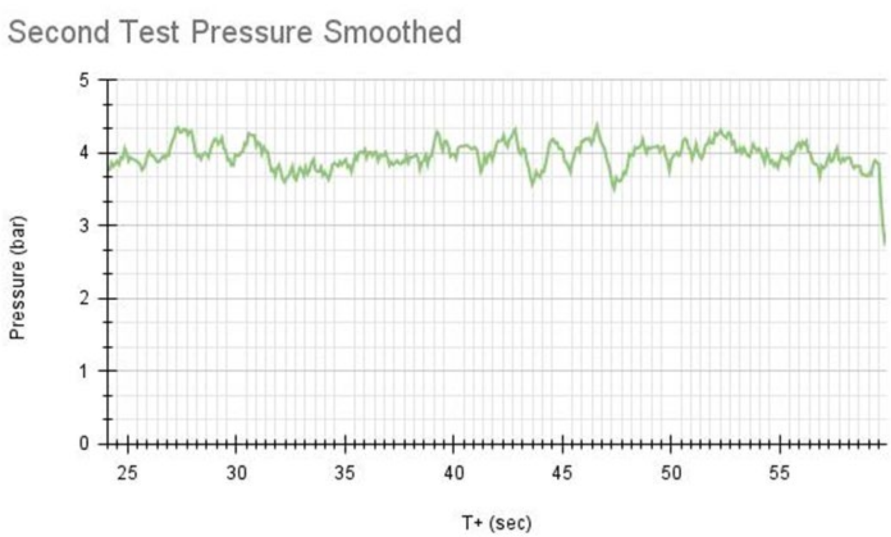
Pressure Findings

The pressure sensor data came in as an analog value and then was run through the equation: = • 0. 0559613 − 2. 07583 . The data received from the pressure sensor was very noisy so it was run through the same smoothing algorithm as the temperature and thrust data.

Second Test Pressure Raw

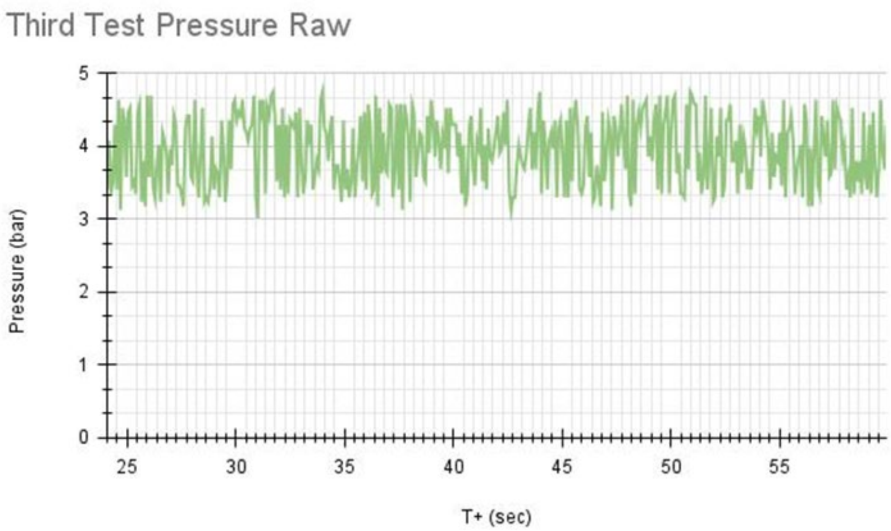


Second Test Pressure Smoothed



In this test, the pressure was relatively consistent and kept around 4 bar of pressure.

Third Test Pressure Raw



Third Test Pressure Smoothed

This test was almost exactly the same as the last test, with the pressure around 4 bar.

Limitations

Throughout my research, I ran into various limitations, three of the largest being: time, resources, and the testing apparatus.

Time

Probably the largest limitation of my research is the time I had to build the engine and the time I had to run tests. If I had more time, I could have been able to build a more complex and refined rocket engine that would have led to stronger findings from testing. Also, if I had more time, I could have run many more tests, further validating any data gathered. However, the fact that I built a functioning engine in such a short time shows how this design is a simple and easy to fabricate engine.

Resources

The most impactful limitation of my entire research project is the resources I have available to me. I was trying to keep the total cost of the entire project under $650, so I had to make necessary cuts on materials purchased. The highest level of nozzle manufacturing I managed to achieve was only lost-PLA-casting instead of the desired metal 3d printed. This is because the cost was too high for me to order it made, and even after I contacted quite a few companies, none of them were willing to help me fabricate the nozzle. Even without the professionally fabricated nozzle, I was still able to perform tests that validated the vortex cooling ability.

Another resource limitation was the computing power I had to run simulations. The CFD simulations I ran were in a cloud-based CFD simulation, which is not as powerful as the simulation software I wanted to use.

Testing Apparatus

The third and final limitation is the apparatus I had to test my engine. This is similar to the limitation of the resources in that I did not have the ability or funds to have a professional test stand and facility. This means there is variability in my data that would not be there if I had a better test stand. The other limitation with my test stand is that I cannot test my engine at different atmospheric pressure, so the aerospike usefulness must be validated through simulations.

Future Research

Future studies that have access to more resources than I did can get the nozzle design fabricated in 3d printed metal have a better test apparatus and invest more time into research. Another possible direction for this project is redesigning the nozzle to be traditionally manufactured with a lathe and a mill. This would be relatively easy and make manufacturing the nozzle out of an aerospace-grade metal much less expensive.

Conclusion

The new understanding created by this research is the validation of a vortex aerospike rocket engine design. This type of exploration into variant rocket engine designs is extremely important for the entire aerospace industry to adopt as current rocket engine design has stagnated in innovation.

This research has filled the gap that there has never been any research into a combined vortex aerospike rocket engine and if it is a viable design for small-scale launchers. This is extremely important because this type of engine is simpler and less expensive to produce then-current rocket engines. As humanity transitions to a more space-focused society and economy, it is vital to have rocket engines that can be mass-produced at a low cost and complexity.

This research has wide-reaching implications for the entire field of rocket engine development. A narrow view shows that a vortex aerospike rocket engine is a design that can work and be used for small-scale launchers. On a wider scale, it shows that combining different separate innovations in rocket engine design can yield a novel and useful idea that can then be applied to the wider industry.

One of this research's wider limitations is that it was not performed in a perfectly controlled environment with top-of-the-line measurement equipment. This is not a major limitation that invalidates my research because the data collected may not have been perfect, but the trends can still be seen, and findings can still be taken from such data.

Future researchers should attempt to make a larger and more refined engine to further validate the design. Specifically, a professionally manufactured nozzle, better injectors, high purity oxygen and propane, and a lighter combustion chamber. A better engine and better testing environment would increase the effect of the findings.

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