The Hybrid Rocket Motor Final Report

ME 140: Advanced Thermal Systems

Team Goblet of Fire

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I. Executive Summary

Our research team was tasked with analyzing and improving a hybrid rocket motor, with a focus on optimizing our motor's specific impulse. We began in MATLAB, estimating theoretical values to set a baseline for future performance. To fabricate the solid propellent, we turned and milled high density polyethylene (HDPE) stock into short cartridges, which we then loaded into a test fire system. Our first test fired successfully, achieving a specific impulse of 134.11 Ns/kg on the stock nozzle. Based on the data, we fabricated a new converging-diverging nozzle, slightly narrower at the throat and long in the diverging section. We tested two new fuel grain designs on the new nozzle, both of which featured a central mixing chamber. Our first design resulted in a powerful test fire (192.77 Ns/kg), but chamber pressure exceeded orifice pressure, and therefore fouled. The third fire, our best legitimate result, achieved 146.06 Ns/kg with a more conservative design. Future efforts would test newer grain designs with the old nozzle, and older grain designs with the new nozzle, to determine the value of both our custom nozzle and the mixing chamber, introduced in test fires two and three. This testing could set the direction for future research.

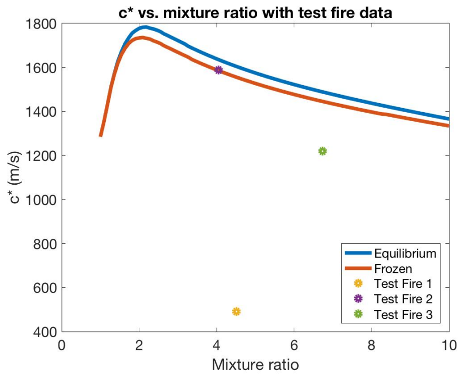
II. Introducing the Problem

Hybrid motors, which combine a liquid oxidizer with a fixed bed of solid fuel, offer distinct benefits for rocket engineers. Hybrid systems are cheaper, smaller, and simpler compared to liquid systems; they are safer and more easily throttled compared to solid systems. Our team was tasked with analyzing and improving a hybrid rocket system, consisting of high density polyethylene (HDPE) solid fuel and propane liquid fuel. We aimed to improve specific impulse, which measures impulse per unit mass of fuel, without "fouling," or having chamber pressure exceed orifice pressure.To improve rocket performance, we machined both HDPE fuel grain stock and graphite stock, for an updated exit nozzle, at the Stanford Product Realization Lab (PRL). Testing occurred at the Stanford ME Research Laboratory (MERL). For analysis, we used MATLAB from Mathworks and Cantera, an open-source software tool for thermodynamics.

III. Analysis and Design

We began our analysis in MATLAB, by plotting c* vs. mixture ratio, by which we determined the mixture ratio that maximized specific impulse. This analysis is reflected in Figures 1 and 2.

In Figure 1, we observe that c* is maximised at a mixture ratio around 2 (2.11 to be precise), which provided the goal for our designs. It is important to note that we aimed slightly higher than this optimum value due to the steep decrease in c* that occurs below the ideal mixture ratio. From the c*, we were able to use Figure 2 to find an ideal expansion ratio for our nozzle (ratio of throat area to exit area), which we observed as 2.36. However in keeping with our aim of aiming for slightly higher mixture ratios we manufactured a nozzle with an expansion ratio of 2.5.



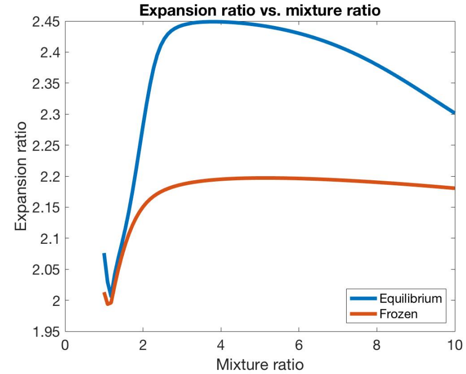
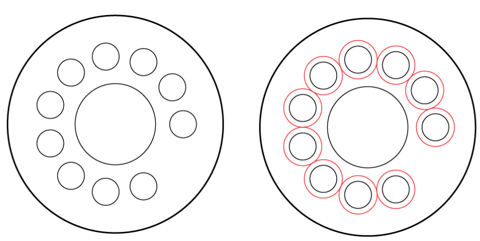


Fig. 1, left: c vs. mixture ratio, with plot points from each of our three test fires.*
Fig. 2, right: expansion ratio vs. mixture ratio.

We opted to extend the diverging section as long as practical in order to maximise the thrust. We also manufactured the largest possible inlet area as this would ensure the fastest possible flow through the throat. This is necessary because of the flow through the throat is not choked (Ma = 1), then the addition of a diverging section after the throat will actually slow the flow when compared to a simply diverging nozzle (which was the design used for the TA nozzle).

To begin design our first iteration of the fuel grain, we took a conservative approach. Our first design consisted of 10 holes sized 0.25” drilled around a larger hole sized 0.75’ in the middle. While drilling the smaller holes around the larger hole, we left a gap between two drilled holes to ensure that there would be no slivering at the end of the burn. We took this conservative approach to the lab and performed our first fire. As expected, we were far from fouling which led us to strive for a more aggressive design.



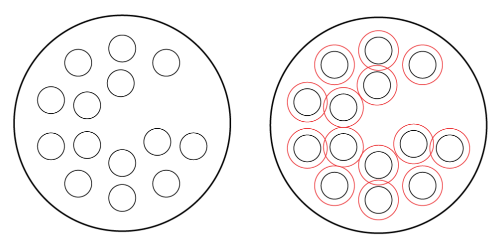


Fig. 3, left: Fuel grain profile A, a more conservative design.
Fig. 4, right: Fuel grain profile B, a more aggressive design.

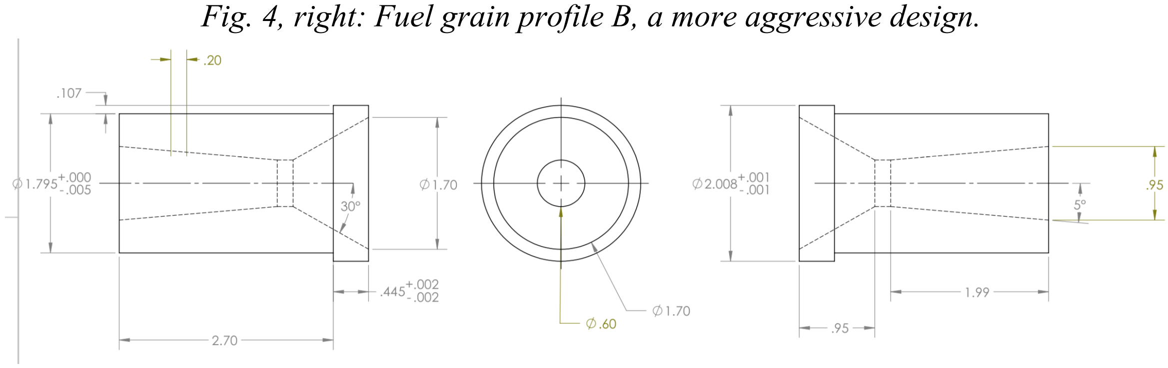


Fig 5: Our custom-built converging-diverging nozzle.

A problem we encountered throughout our design process was that of low regression rates, which is a common effect of using hybrid rockets. Our first test fire had a regression rate of around 0.51*10^-4 m/sec for an oxidizer fuel ratio of 0.15. In order to mitigate this problem, we could increase the oxidizer flow speed or increase the surface area available for burning through each design iteration. To further better our regression rate, we also increased the amount of heat transfer by introducing turbulence with a mixing chamber. When we focused solely on this design parameter, we opted for the aggressive fuel grain option that was alluded to previously. It gave us a regression rate of 0.77*10^-4 m/sec, but it came at a steep price.

IV. Manufacturing

In order to implement updated designs, we machined both fuel grain stock and graphite stock (for the nozzle). To process stock HDPE, we turned segments of stock in the lathe down to a diameter of 2.010±0.002", per project specifications. These specs also set a length of 5.375±0.015". Early efforts accurately machined HDPE within tolerance limits, but we soon learned that no drill bit - mounted on the mill or drill press - could drill pores through that much material without wandering. As such, we quickly learned to split our 5.375" segment into small pieces, aligning the pores inside the test fire chamber instead of fabricating a single block of fuel. This switch to segmented machining increased manufacturing time per fire, but also increased accuracy and accomodated greater flexibility in our designs, including the mixture chamber for test fires two and three.

We machined our first fuel grain on the drill press, using a laser cut Duron template as a guide for port placement. In order to increase efficiency and precision, we machined the second and third fuel grains on the mill, using coordinates from our Adobe Illustrator files to determine the location of each of the ports. The second and third fuel grain designs also included a central mixing chamber, which we machined on the lathe. Both material frustrations and an intricate design complicated the machining of the graphite nozzle, but we were able to manufacture our nozzle without too many obstacles.

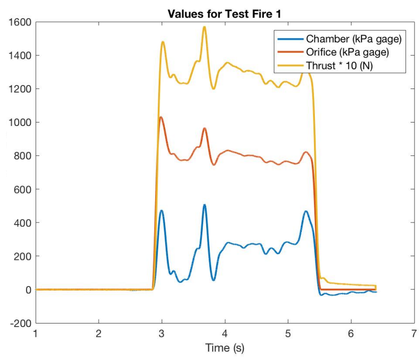
V. Testing Results

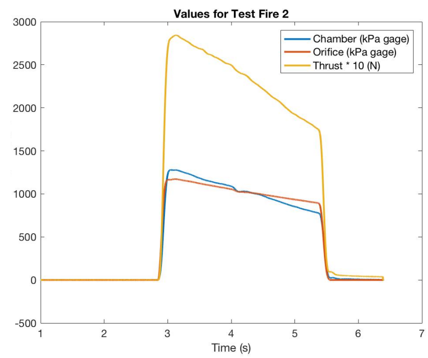
Our first test fire featured fuel grain profile A, with no mixing chamber, and fired on the course-provided stock nozzle. The fire avoided fouling and recorded a specific impulse of 134.11 Ns/kg. We observed that we were safely under the fouling limit and had a mixture ratio in our desired range, which gave us freedom to be more aggressive for our subsequent fuel grain designs, and also to optimize by adding our C-D nozzle. Also, as shown in Figure 6, the data for a our first fire was sadly noisy, which made it difficult to make concrete qualitative judgements about the performance beyond the Isp value.

Our second test fire featured fuel grain profile B, with a mixing chamber, and fired on our custom-built nozzle. The fire recorded a specific impulse of 192.77 Ns/kg, but slightly exceeded the pressure threshold, and fouled, and Figure 7 shows the pressure and thrust for this fire. Our third test fire featured fuel grain profile A, now with a mixing chamber, and fired on the custom-built nozzle. This more conservative design did not foul, and moderately improved on the first fire, recording a specific impulse of 146.06 Ns/kg. This third fire was our best legitimate result, however Figure 8 shows that considerable improvement in chamber pressure could have been made without fouling.

Test Fire No.	Fuel Grain Profile	Mixing Chamber	Nozzle	Specific Impulse (N*s/kg)	Foul?
1	A	N	Course-provided	134.11	N
2	B	Y	Custom-built	192.77	Y
3	A	Y	Custom-built	146.06	N

Table 1: Test fire results.





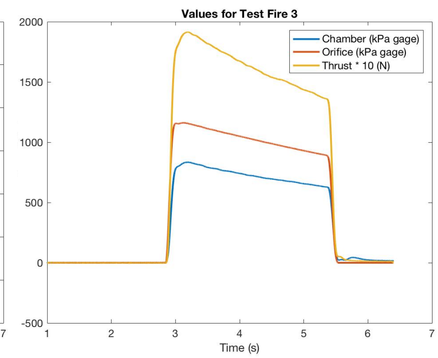


Fig. 6, left: chamber pressure, orifice pressure, and thrust vs. time for Test Fire 1
Fig. 7, center: chamber pressure, orifice pressure, and thrust vs. time for Test Fire 2
Fig. 8, right: chamber pressure, orifice pressure, and thrust vs. time for Test Fire 3

VI. Findings and directions for future research

Our design refinements, and subsequent experimental results, helped develop strong intuitions for hybrid rocket motor design. First, we observed that a large number of pores seemed to be the most effective. While these designs do introduce slivering concerns, they were never an issue during our fires. Second, our second test fire was the best performer, but test fire three avoided a foul. We would pursue a "Goldilocks grain," which is somewhere between the profiles of the two fuel grains. We could also sand down the nozzle to remove sharp edges, which may improve performance. Third, while we know that test fire three improved on test fire one, the given experimental data cannot confirm to what extend a mixture chamber or updated nozzle design impacted specific impulse. To identify how each revision changes our target parameter, we would go back and test fire a fuel grain with profile A and no chamber (identical to test fire one) on the new nozzle, and a fuel grain profile with profile A and a mixing chamber (identical to test fire three) on the course-provided nozzle. The following results would likely validate the further refinement of either our mixing chamber or nozzle.