Production of Wax Fuel Grains for a Hybrid Rocket Motor

Ian Charter,1 Jose De Lara,2 Paul DeTrempe,3 Christine Mehr,4 Samantha Paige,5 and Lui Suzuki6

University of Illinois at Urbana-Champaign, Urbana, IL, 61801

This paper covers the development of paraffin wax fuel grains for a small, student-designed, hybrid rocket motor. To create the grains, an improvised rotary apparatus was employed and tested using varying sealing mechanisms and cooling times. The grain creation process consisted of several iterations, each covered in this paper, before arriving at its current design. A small tabletop lathe, horizontally oriented rotary system, and live center ensured stable rotation of the grain throughout the hardening process. The discussion will center on design requirements of the fuel grains, decided methods for their creation, and the quality of grains fabricated using the various techniques. Results from tests are introduced, quantified, and displayed within.

I. Introduction

This paper presents an overview of the method for the creation of paraffin wax fuel grains for Illinois Space Society’s Hybrid Rocket Engine at the University of Illinois at Urbana-Champaign. The grains will be used in future test and launch firings of the school’s first hybrid rocket motor. Hybrid rocket engines provide the thrust control of liquid engines with the safety factor and simplicity of solid engines. They also have on-demand termination, can be reignited if needed and relatively high specific impulse. Mass production of hybrid engines could substantially lower the cost of suborbital flights, making high atmosphere and suborbital flights accessible to more scientists and engineers for a variety of experiments. The ISS team explored effective methods for creation of high quality, low cost grains for their own engine, though improvements in grain creation could have wide reaching effects.

II. Motivations for System Design

The goal of the ISS hybrid rocket project was to construct a modular, rapid reuse hybrid rocket motor to eventually fly in a large rocket test apparatus. Paraffin wax was chosen to be the solid fuel grain for the hybrid rocket engine because of the ease of shaping the grains, availability, and energy density. The team’s goal was to create a cylindrical paraffin wax fuel grain, hollow in the center to allow nitrous oxide flow for combustion. The primary method considered was a simple mold set up. The team would pour liquid paraffin into a cylindrical mold, wait for it to harden, and drill a hole down the center. However, research by the team indicated that paraffin shrinks substantially when cooling, which would lead to an uneven distribution of wax throughout the grain as well as a suboptimal grain length. The mold system was also ruled out for its high risk of cracking the wax, and poor grain geometry at borders with the mold walls.

For these reasons, it was decided that the grains should be spincast, or spun while hardening, to avoid the above issues with mold casting. By spinning a tube with melted paraffin wax inside of it, the wax would push against the outside of the tube because of the centrifugal force. As the wax hardened and shrunk, the free volume inside of the tube would increase while the grain slowly hardened from the outside in. This outside-in hardening leads to a constant outer diameter to help reduce oxidizer leakage and a smooth inner tube going down the middle of the fuel grain, conducive to even burning during combustion.
III. Initial System Design for Grain Creation

The contraption used to create a paraffin wax fuel grain comprised of polyvinyl chloride (PVC) end caps fitted at the end of an acrylic tube. The acrylic tube was chosen as the grain casing for cost efficiency, ease of manipulation, and for the convenience of matching the diameter of the combustion chamber for a smooth, but snug, fit. The team also chose the acrylic to meet the project goal of rapid reusability. With grains spun within standard tubes, the team was able to quickly switch out old grains for new following test fires and launches, without the need to switch out the entire combustion chamber and associated components. The acrylic tube came in 36 inch lengths, which were easily cut down to the desired 5.375 inch lengths using resources available in the Engineering Students Projects Lab (ESPL). For initial system design, the team planned to simply attach the end caps snugly over the acrylic fuel grain, using a press fit and the natural friction between the end caps and the fuel grain to seal the acrylic grain shut. This system was initially chosen for its simplicity and compatibility with available hardware, namely a small lathe available for student groups in the Department of Aerospace Engineering. In addition, this set up allowed visual feedback of grain progress in areas not obstructed by the end caps, due to the transparency of the acrylic tube and melted paraffin.

Only minor modifications were required to make this basic set-up viable. Firstly, the insides of the end caps were widened via trimming and sanding. This modification accounted for a slight discrepancy between the inner diameter of the end caps and the outer diameter of the acrylic. The team trimmed the end caps until a tolerance tight enough for press-fitting was achieved.

![Figure 1. End caps for sealing acrylic tube and spinning grain. Left cap modified to fit in lathe attachment](image1)

![Figure 2. First attempt at fuel grain with large inner diameter and rough surface](image2)

IV. Modifications for Grain Improvement

Through the construction process of the fuel grains, each new grain presented an unforeseen issue. Each issue was addressed in succession leading to eventual satisfactory grain creation. The first attempt involved holding one of the end caps with the chuck of the lathe and while the other unsupported. The tailstock of the lathe was butted up against the unsupported end cap to prevent end cap separation during the spin. This forced the cap into the jaws and attempted to prevent the unattached end from sagging down. The tube was then spun at approximately 700 rpm for just over an hour. At that time the lathe started to shake as the tailstock began to melt the end cap due to the friction between the pieces. This forced the casting process to be stopped and caused the team to reevaluate the setup. Even though the process was stopped early, an initial grain had been cast. This grain had a very rough surface as well as a large diameter hole down the center due to the large quantity of unmelted wax. This first grain is shown in Figure 2. The rough surface led the team to believe that the lathe was spinning too slowly, causing clumps of wax to form while hardening.

On the second attempt the assembly was attached onto the lathe and pushed in via a fixed metal pin in the tail stock. The pin in the tailstock pressed into a corresponding metal cap pressed into a modified fuel grain end cap. The lathe was then spun at approximately 2300 RPM, which was chosen because it was the rotational speed at which all the paraffin wax was visibly pushed towards the outside of the acrylic tube evenly. The acrylic tube was spun for about 20 minutes. At that time, the lathe started to shake as the tailstock began to melt the end cap due to the friction between the pieces. This forced the casting process to be stopped and caused the team to reevaluate the setup. Even though the process was stopped early, an initial grain had been cast. This grain had a very rough surface as well as a large diameter hole down the center due to the large quantity of unmelted wax. This first grain is shown in Figure 2. The rough surface led the team to believe that the lathe was spinning too slowly, causing clumps of wax to form while hardening.
Throughout the test, team members periodically removed the assembly from the lathe to determine whether the wax inside had hardened or not. This was done by shaking and feeling the weight transfer in the tube because the inside of the tube could not be seen. Though both the acrylic tube and liquid paraffin were transparent, hardened paraffin wax lining the outside edge of the acrylic tube increased significantly in opacity. Team members checked a few times and once the wax was thought to have completely hardened, the PVC caps were removed to observe the fuel grain in the interior.

Following the second test, the team then switched to a live center pressing inwards on the unsupported end of the fuel grain. Due to its spinning tip, the live center allowed the point of contact with the tail stock to rotate along with the plastic end cap, reducing if not eliminating the frictional heat imparted on the plastic end cap. The live center is visible in Figure 5 A notch was made in the end cap as an inset of the live center. In the third attempt, one layer of wax paper and one layer of duct tape was put between the acrylic tube and endcaps. Duct tape was also wrapped around the endcap/acrylic interface and all the way around the tube to prevent leakage similar to the previous test. After 6 hours spinning at 2200+ rpm, the grain was shaken to feel for any liquid paraffin left sloshing around inside. After determining that the wax had all solidified, the endcaps were removed and the fuel grain was observed. The wax was fully hardened but inner cylindrical hole was wider than expected. The duct tape on ends of the acrylic tube had also melted due to the high temperature of the melted wax, causing a substantial amount of wax to leak into the endcaps. The extra wax in the endcaps can be seen in Figure 6. Even with some wax loss though, the texture of the inner and outer faces of the fuel grain was smooth and satisfactory. The actual ends of the hardened fuel grain were not perpendicular to the acrylic tube, but curved somewhat. The end away from the lathe (the live center end) bulged out in a convex manner while the end closer to the spinning lathe had a concave shape. It was hypothesized that this was caused by precession of the grain during the imperfect spinning process, but it may be caused by other factors not mentioned here.

Figure 3. Lathe setup for 2nd grain test with tail stock set up on the right side. Wax buildup down the middle of the lathe caused by leakage while spinning the grain

Figure 4. Fuel grain sealed with duct tape over ends (duct tape melted causing leaks)
In the fourth attempt the ends of the tube were sealed with one layer of wax paper without duct tape due to the melting that had occurred previously. To prevent wax from leaking into the endcaps, the endcaps were preemptively filled with wax and left to harden so there would be no volume in the endcaps for the wax to seep into. As an unintended consequence of the preemptive end cap filling, it was much harder to fit the end caps onto the acrylic tube during this attempt. Because of the tougher fit, the team struck the end cap with a mallet, ripping the wax paper and leaking wax into the end caps. To prevent a repeat of this leakage, the cap was removed, the wax paper and wax replace, and the end caps instead pushed onto acrylic tube gently and slowly, allowing trapped air to escape and mitigating the risk of a wax paper tear. The second try in putting on the endcap with this method worked successfully. After the caps were put on, duct tape was wrapped around endcap/acrylic
interface to prevent leaks, as done previously. The wax was spun for 5 hours at 2200+ rpm until it was completely hardened and the resulting fuel grain came out well. This successful fuel grain is shown in Figure 7.

The end caps were removed more easily than in prior tests, and the fuel grain had a smallest inner diameter yet. The grain had the smooth inner and outer diameters desirable for the ISS hybrid team’s purposes. Just as in the previous test, the grain had substantial bulging on the live center side and indentation on the lathe side. It also had areas on the outer diameter where the wax appeared to have slightly separated from the acrylic tube, indicated by clear “bubbles” at the outside of the grain. The subsequent fifth fuel grain used the same procedure and also yielded satisfactory results, so the team has chosen this as a simple method for manufacturing consistent fuel grains to be burned.

V. Conclusion

Succeeding the five trials of spin casting, five paraffin fuel grains of improving quality were successfully produced, and a system for producing consistent, high quality grains was devised. Through some problem solving and design iteration, the grains developed from leaky, wobbly, and incomplete to smooth and complete. This technique for grain development, in its most recent iteration, will be used by the ISS hybrid team in their rocket engine for many more test firings and launches, helping to achieve the goal of a modular, high-powered, yet simple hybrid rocket engine.

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