Additive Manufacturing Of Fuel Grains For Hybrid Rocket Motors For Increased Efficiency

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***Abstract*—This paper provides the fundamental, working mechanisms of combustion and history of hybrid rocket engines. It is discovered that the primary parameter in the performance and design of a hybrid rocket lies in the fuel grain regression rate. Large scale application of hybrid rocket engines has considerably lower regression rates compared to solid and liquid rockets. The paper explores studies in regression rates and its many corresponding, influential factors while providing solutions to increase the performance and efficiency of hybrid rockets. Additive manufacturing methods provide opportunities to fabricate fuel grains with helical port which enhances heat transfer significantly and in effect contributes significantly to increasing the fuel grain regression rate.**

Keywords—combustion, regression, rate, solid, flame, boundary layer, convection, conduction, engine, rocket, hybrid, helical, additive manufacturing, HTPB

1. Introduction

A hybrid rocket combines advantages of both liquid and solid rockets. In a convention liquid bi-propellant chemical rocket, both the fuel and oxidizer exist as liquid form in separate tanks and fed into a combustion chamber where combustion is primarily limited by pressurization, system controls mass injection, and mixing rate. Liquid propellants typically require turbo-pumps and complex plumbing controls to generate high mass flow rates and uniform fuel-oxidizer mixture at the combustion chamber. Liquid rockets are efficient and performance systems but costly due to the complexity of controls and plumbing. Solid rockets are mechanically much simpler compared to liquid rockets since in solid rockets the liquid and oxidizer exist in a single solid-phase propellant grain. Combustion of well-mixed solid-phase propellant grain is primarily dependent on direct heat transfer from flame to surface. With solid rockets, the manufacture of the propellent itself is expensive and requires costly vehicle design to accommodate the challenges in thrust control and termination. The propellant is an explosive mixture and proves challenging in abort procedures. The hybrid rocket consists of a liquid oxidizer and a solid fuel grain, merging the operational flexibility and safety of liquid rockets and simplicity of solid rockets. The fuel and oxidizer are contained separately within the propulsion system, and the fuel grain itself is inert. In addition, throttling is more manageable compared to liquid rockets since fuel flow rate is dependent on oxidizer flow rate instead of synchronizing and throttling two separate flow rates. [1]

The history of hybrid rockets extends through the early 1930s where the development of both solid and liquid rockets occurred. In 1933, Soviet rocket engineers Sergei P. Korolev and Mikhail K. Tikhonravov reported on a flight made by the GIRD-09 hybrid rocket engine utilizing gelled gasoline and liquid oxygen, LOX. In Germany 1937, unsuccessful combustion tests were performed by I.G. Farben using coal and gaseous N_2O. The lack of performance was due to poor burning rate resulting from carbon's high heat of sublimation. Continuing from the late 1940s through 1956, General Electric engineers George Moore and Kurt Berman utilized both analytical and experimental approaches in exploring hybrid rocket engines. 100 of 300 tests performed using polyethylene, $(C_2H_4)_n$, as fuel and 90% hydrogen peroxide, H_2O_2, as oxidizer were characterized as a rod and tube configuration. Moore and Berman concluded some fundamentals in design: 1) Grain cracks had no effect on combustion 2) there exists longitudinal uniformity of burning 3) throttling was achievable using a single valve, the oxidizer valve 4) a high liquid to solid ratio was required, among other findings. Reverse hybrid rockets were investigated as early as 1952 where William Avery and colleagues at the Applied Physics Laboratory of John Hopkins University utilized solid oxidizers (potassium perchlorate, ammonium, nitrate, and ammonium perchlorate), and liquid jet propellant (JP). As understood then and still now, major problems encountered using reverse hybrid systems are experimentally characterized by poor combustion behavior and at the very least negligible improvement in performance to justify challenges in developing sufficient solid oxidizers. By the 1960s, significant studies and experiments resulted in considerable accomplishments that would shape hybrid rocket engine design concepts moving forward. Among the highlights however, critical gaps and disadvantages were identified. [2]

Hybrid rockets are insufficient systems. Regression rate, the key parameter influencing design of hybrid fuel grain, is the rate at which the fuel surface recedes over the course of a burn and is typically 25 – 30% lower [3] in hybrid rocket motors compared to solid fuel motors in the same thrust class. Hybrid rockets are characterized by poor combustion efficiency due to the oxidizer and fuel mixing at the macroscopic scale. The mechanism of fuel melting, evaporation, and diffusive mixing is a slow combustion process and varies downstream of the fuel port. Due to this low regression rate, large grain surface area are needed to supply the required thrust, meaning having to develop multiple ports into the fuel grain leading to low volumetric fuel loading for each rocket engine.

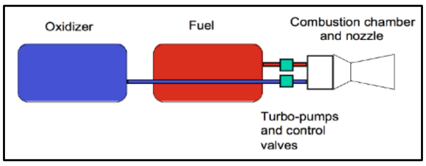

Figure 1 – Liquid Propellant Rocket System

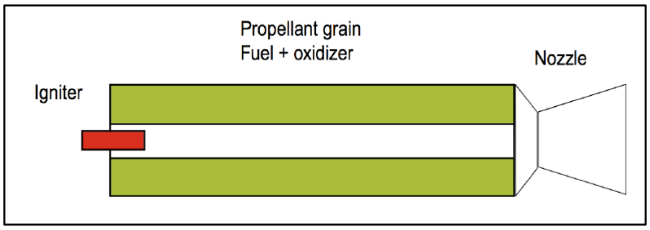

Figure 2 – Solid Propellant Rocket System

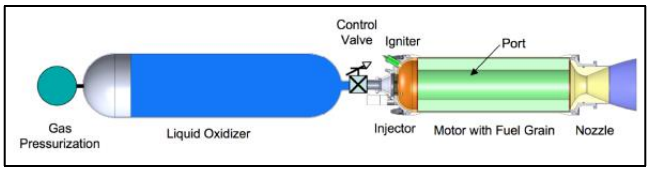

Figure 3 – Hybrid Rocket System

2. Hybrid Rocket Combustion

2.1. Boundary Layer Combustion

In classical hybrid motors, the liquid oxidizer is typically injected through a pre-combustion chamber for vaporization before heading to the head-end of the fuel grain combustion port. After ignition, the fuel grain experiences pyrolysis, defined as the solid-to-gas phase change that involves polymer chain breaking reactions that occur near-surface region when fuels recede. The pyrolyzed gaseous fuel and oxidizer mixes and reacts along the length of the fuel grain port and undergo mixing and combustion toward aft of the combustion chamber near the nozzle and expelled out to generate the necessary thrust. Unlike liquid rockets where combustion occurs at the droplet scale and unlike solid rockets where combustion occur at the surface of the propellant grain, combustion in hybrid rocket motors occur in a turbulent boundary layer, specifically a flame zone boundary layer.

The boundary layer develops over the fuel grain port surface due to the injection of oxidizer at the head of the motor. The boundary layer is characterized by strong velocity, temperature, and species gradients normal to the surface, however mass, momentum and energy transport are dominated by the turbulent flow. There exists deep in the momentum boundary layer a fuel rich flame thickness. According to Marxman and Gilbert, the engineers who originally developed the first method characterizing hybrid rocket fuel regression rate law in the 1960s, the location of this flame region resides at approximately 10 – 20% of the boundary layer thickness above the fuel grain surface. [1] The pyrolyzed fuel vapor is then transported to the flame zone by convection and diffusion and mixes with the gaseous oxidizer. This is additionally supported by turbulent diffusion from oxidizer mass transfer.

At the fuel grain surface, polymer degradation is taking place. The nature of its surface roughness and possible mechanical deformations due to chamber pressures can affect heat transfer. In specific cases, a liquid melt layer may form on the surface in the absence of sufficient energy. The decrease in regression rate is evident due to pyrolysis which blocks the heat transfer to the surface, but the blowing effect of the injector weakens this blockage allowing more heat to reach the surface. This cyclic mechanism is the primary characteristic for combustion of hybrid rockets. [4]

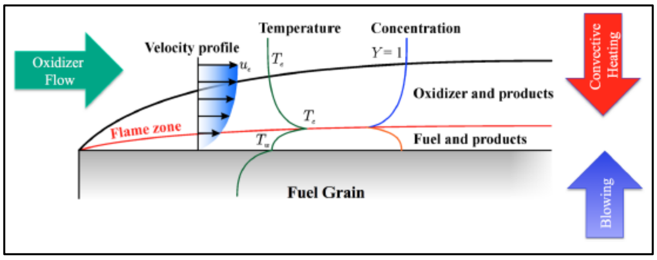

Figure 4 – Boundary Layer Combustion

2.2. Regression Rate

G.A. Marxman's theory is significant in that it identifies the key factors influencing regression rate and their relationships such as convective and conductive effects, blocking effect as stated earlier, and so on. The theory is that fuel regression rate is proportional to the mass flux averaged across the port, and independent of pressure. The mass flow rate increases radially and axially along the port leading to coupling between fuel regression rate and local mass flux. A popularly used expression for regression rate is as follows:

General Expression of Marxman's regression rate, $\dot{r} = aG_{ox}^{n}$ **(1)**

Where a and n are empirically determined, a representing a function of space and space and n as a function of the chosen fuel grain and oxidizer materials (about n ≈ 0.8). However, since most practical hybrid motor designs employ a cylindrical configuration, the standard practice is to invoke characteristic length of the port.

$$\dot{r} = aG_{ox}^{n}x^{m} \quad \textbf{(2)}$$

Where x is the distance along the port and m, like n function, is propellant dependent. As mentioned in previous section, regression rate is a velocity and typically expressed in millimeter per second.

Regression rate data are typically gathered from smaller scale fuel-oxidizer testing and plotted against the oxidizer mass flux G_{ox}. [x] A non-linear regression algorithm is employed to compute regression rate law coefficients and exponents from ground-based testing for literature. In addition, modern tests implement ultrasonic or x-ray techniques to directly measure instantaneous regression rates.

The most common fuel used in many modern experiments and studies is hydroxyl-terminated polybutadiene, also known as HTPB. It is a type of synthetic rubber based on polybutadiene monomers. It is the most popular among universities and hobbyists due to its cost and commercial availability.

With results published in 2006, Greg Zilliac and M. Arif Karabeyoglu from NASA Ames Research Center attempted to further explore regression rates in hybrid rocket motors by expanding on Marxman's regression rate laws and developing a computational fluid dynamic (CFD) model to simulate the related modules. [5].

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In Zilliac's paper, grain configuration and port entrance effects are included in the regression rate models, which are factors that influence the magnitude of average mass flux exponent, n. Several non-dimensional numbers were discussed summarized in Table 1 below:

Table 1 – Dimensionless parameters

Non-dimensional Number	Definition	Physical Meaning	Typical Value	Interpretation
Prandtl	$\Pr = \frac{c_p \mu_e}{k_g}$	$\frac{\text{momentum diffusivity}}{\text{thermal diffusivity}}$	≈ 1	Approximately the ratio of the velocity boundary layer thickness to the thermal layer thickness.
Schmidt	$Sc = \frac{\mu_e}{\rho D_{12}}$	$\frac{\text{momentum diffusivity}}{\text{mass diffusivity}}$	≈ 1	
Lewis	$Le = \frac{Sc}{\Pr} = \frac{k}{\rho_e c_p D_{12}}$	$\frac{\text{thermal diffusivity}}{\text{mass diffusivity}}$	≈ 1	Note that in some references $Le = \frac{\Pr}{Sc}$
Stanton	$St = \frac{Nu}{\operatorname{Re}\Pr} = \frac{h}{\rho_e u_e c_p}$	$\frac{\text{heat transferred}}{\text{fluid thermal capacity}}$	$<<1$	Modified Nusselt number
Nusselt	$Nu = \frac{hL}{k}$	$\frac{\text{total heat transfer}}{\text{conductive heat transfer}}$	$>>1$	Dimensionless temperature gradient at the surface.
Damkohler	$Da = \frac{\tau_t}{\tau_c}$	$\frac{\text{fluid dynamic time scale}}{\text{chemical reaction time scale}}$	$>>1$	$Da >> 1$ implies diffusion controlled combustion
Reynolds	$\operatorname{Re} = \frac{\rho_e u_e L}{\mu_e}$	$\frac{\text{inertial force}}{\text{viscous force}}$	$>>1$	

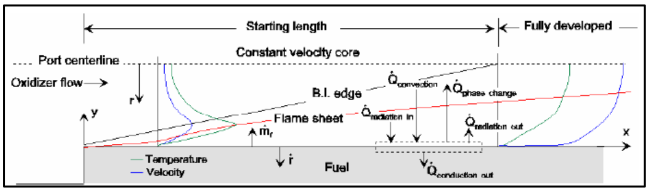

Figure 5 – Zilliac's Conceptualization of Flow and Energy Balance within hybrid rocket motor

The focus of Zilliac's paper is that the approximation of a thin flame sheet forms within a boundary layer on the fuel surface implies that all chemical reactions are confined to this thin sheet. It is a fairly safe assumption that the boundary layer flow in the port is turbulent from inception because of the transpiration of fuel from the surface. To simplify the analysis, boundary and thermal layer similarity is assumed resulting in fuel and oxidizer concentration profiles that are linearly dependent on the velocity profile. At the fuel surface, the steady-state energy balance as shown:

$$\dot{Q}_{convection} + \dot{Q}_{radiation\ in} = \dot{Q}_{conduction\ out} + \dot{Q}_{phase\ change} + \dot{Q}_{radiation\ out} \quad (3)$$

The above can written as per unit surface area in Equation 4 below:

$$k_g \frac{\partial T}{\partial y}\Big|_{y=0^+} + \alpha \varepsilon_g \sigma T_f^{\,4} = k_f \frac{\partial T}{\partial y}\Big|_{y=0^-} + \rho_f \dot{r} h_g + \varepsilon_s \sigma T_s^{\,4} \quad (4)$$

Where h_g is the effective heat (enthalpy) of gasification. At the fuel surface, the rate of heat transfer per surface area convected from the flame sheet to surface is equal to that conducted and therefore the simplified fuel surface energy balance can be written as:

$$\dot{Q}_s = \rho_f \dot{r} h_g \quad (5)$$

Zilliac also performed a literature review of hybrid rocket fuel burn test results from a variety of different grains using oxygen as the oxidizer. Figure 6 and Table 2 show the average regression rate for various commonly used fuels. Figure 7 is Zilliac's modeled average of regression rates for similar fuel types.

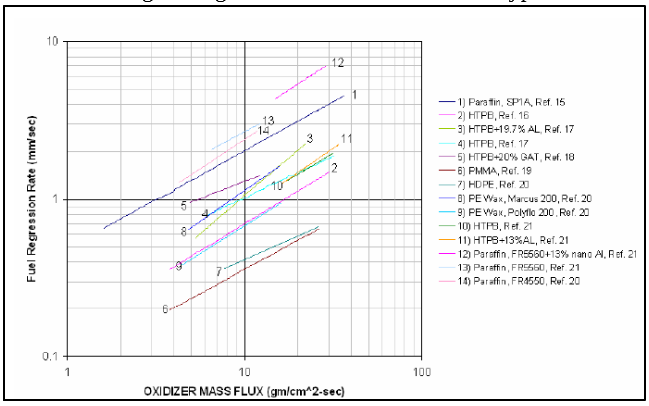

Figure 6 – Average fuel regression rate with oxygen

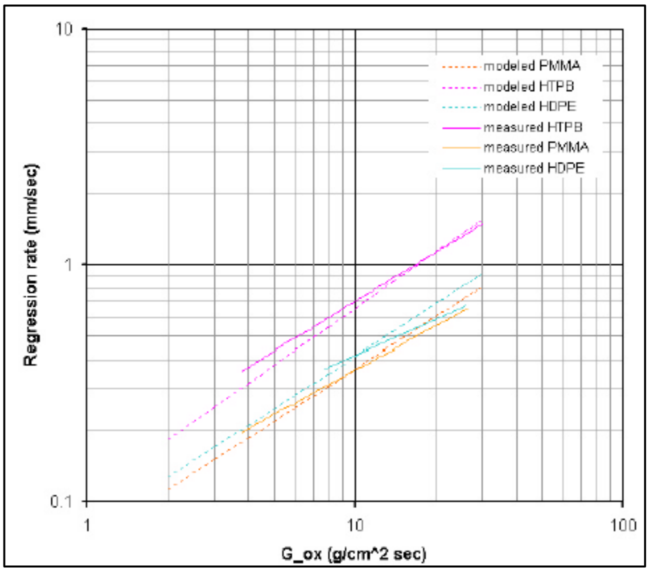

Figure 7 – Modeled average fuel regression rate with oxygen.

Table 2 – Captured data from regression rate tests

Results summary of the average regression rate with oxygen for various fuels								
No.	Fuel	a †	n	No. of Tests	Chamber Pressure Range (MPa)	Average O/F Ratio Range	Data Reduction Technique	Oxidizer Mass Flux Range (g/cm^2-sec)
1	Paraffin, SP1A	0.488	0.62	65	1.1-6.9	1.0-4.0	DA	1.6-36.9
2	HTPB, (Thiokol)	0.146	0.681	16	-	-	-	3.8-30.2
3	HTPB+19.7%AL	0.117	0.956	2	1.2	-	OA	5.1-23.0
4	HTPB	0.304	0.527	3	2.0	-	OA	6.2-31.0
5	HTPB+20%GAT	0.473	0.439	5	-	-	-	-
6	PMMA	0.087	0.615	8	0.3-2.6	-	-	3.3-26.6
7	HDPE	0.132	0.498	4	0.7-1.3	3.8-5.9	DA	7.7-26.1
8	PE Wax, Marcus 200	0.188	0.781	4	0.5-1.2	2.2-3.2	DA	4.8-15.8
9	PE Wax, Polyflo 200	0.134	0.703	3	0.6-1.2	1.6-1.7	DA	4.4-16.3
10	HTPB	0.194	0.670	6	-	-	OA	17.5-32.0
11	HTPB+13% nano Al	0.145	0.775	12	-	-	OA	16.5-34.2
12	Paraffin, FR5560 + 13% nano Al	0.602	0.730	8	-	-	OA	14.5-29.0
13	Paraffin, FR5560	0.672	0.600	4	-	-	OA	6.3-12.3
14	Paraffin, FR4550	0.427	0.748	3	0.7-?	1.3-1.8	DA	4.3-11.9

Regression rate equation: $\bar{\dot{r}} = a\bar{G}_o^{\,n} x^m$ with $m = 0$

† For use with G_o with units of gm/cm^2-sec, produces an average regression rate in mm/sec.

DA: Diameter Averaged, FA: Flux Averaged, AA: Area Average, OA: Other averaging technique applied

The comparisons are shown to be reasonable given the level of approximation in the model but additional work is required before models will overtake regression rate measurements. [6]

In 2013, University of California, Irvine published a paper in the Journal of Propulsion and Power Vol. 29 which defined a model of solid-fuel regression rate for hybrid rockets with experimental support from the Space Propulsion Laboratory of the Politecnico di Milano (Polytechnic University of Milan). The program tested a formulation of HTPB as well and using gaseous oxygen. The experimental activity involves a method of ignition using a high-powered CO_2 laser for over 40 tests conducted at different pressure ranges, fixed at injection temperature of 298K. The test sets consisted of HTPB fuel formulation cylindrical samples (20 mm in external diameter and a central port diameter of 4 mm, length of 30 mm). A simplified analytical model was developed and presented in this paper corresponding a pressure dependency for regression rate. The results are shown Figure 8 at each atmospheric trial set.

Figure 9 depicts regression rates as a function of specific mass flow pressure value by interpolation. The figure exhibits negligible pressure dependence as called out Section 2.2 of this document.

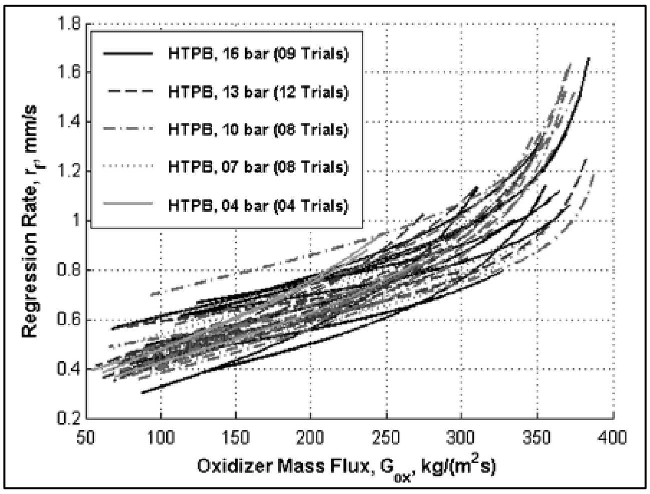

Figure 8 - Comparison of instantaneous regression rate for all the tests showing similar trends

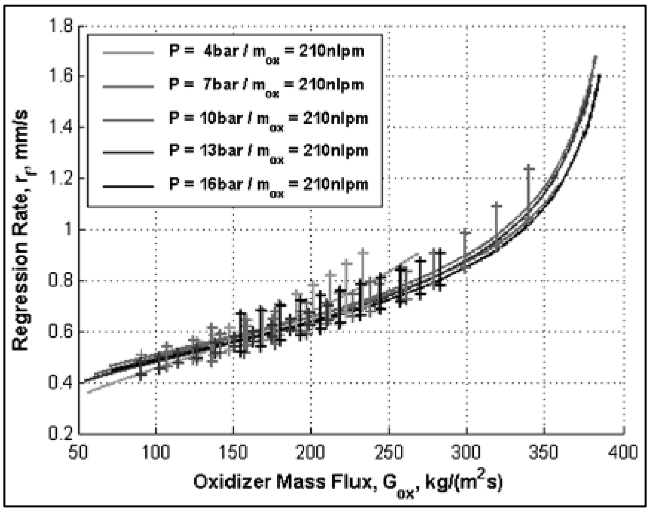

Figure 9 – Instantaneous ensemble regression rate showing negligible pressure dependence

3. Additive Manufacturing of Fuel Grain and Helical Port Structures

3.1. Comparing ABS to HTPB

Ways to increase regression rate of HTPB fuel are to develop creative methods to increase surface within the fuel grain.

In 2013, Stephanie Whitmore and coworkers from the Utah State University investigated the use of acrylonitrile butadiene styrene (ABS) as rocket fuel material. ABS is a type of thermoplastic, widely mass-produced for non-combustion applications including household plumbing and structural materials such as the spool of extruded material for rapid prototyping, more commonly referred to 3D printing. ABS has several mechanical properties, including its ability to be made into a variety of configurations using fused deposition modeling (FDM). [7]

When heated, ABS forms a liquid layer providing significant amount of cooling along the burning surface. In theory, using ABS as fuel grain provides some self-cooling property to external motor case during the burn. Under certain conditions, these liquid droplets may serve to damp non-acoustic and acoustic flow instabilities in the combustion chamber.

From a mechanical standpoint, ABS has yield strength that is 38% of aluminum (high structural modulus, 2.4 GPa). And will allow the fuel grain to take a significant portion of the any environmental pressure loads, reducing wall thickness requirements.

From a chemical combustion standpoint. Whitmore and co. initially developed a numerical plan to quantify the material's standard enthalpy formation. The enthalpy of formation is required to calculate combustion products when burned. A comparison is shown between HTPB and ABS using nitrous oxide, N_2O. Figure 10 plots the calculated flame temperature of HTPB and characteristic velocity as a function of oxidizer-to-fuel ratio, O/F at each given pressure conditions. Figure 11 plots the calculated flame temperature of ABS and characteristic velocity as a function of oxidizer-to-fuel ratio, O/F at the same pressure conditions.

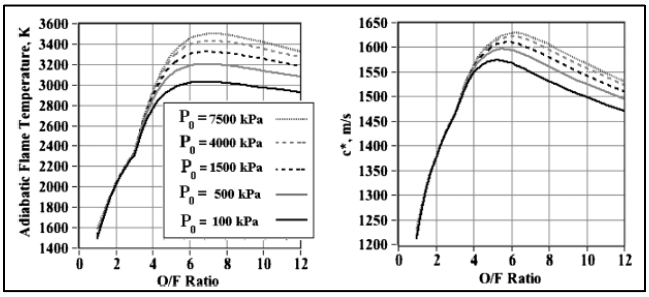

Figure 10 – Thermodynamic and transport properties of N_2O/HTPB combustion products

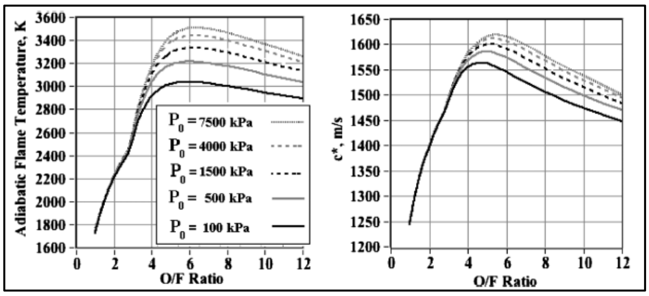

Figure 11 – Thermodynamic and transport properties of N_2O/ABS combustion products

When comparing the N_2O/ABS thermodynamic and transport charts to the corresponding HTPB charts, the propellant characteristic velocity of ABS is less than 1% lower than HTPB and that the peak velocity values tend to occur at lower O/F rations, between 4.0 and 5.5 compared to HTPB where optimal values lie between 5.0 and 6.0. This means that lower ABS-motor oxidizer flow levels produce equivalent performance to HTPB motor.

The experiment uses geometrically identical fuel grains cast from HTPB and ABS. The test cases were fired in a Utah State University. Figure 12 shows fuel grain dimensions. Measurements obtained include chamber pressure, thrust, total impulse, motor

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case temperatures, exhaust temperatures, specific impulse, mass flow rate, consumed propellant mass, and propellant regression rate.

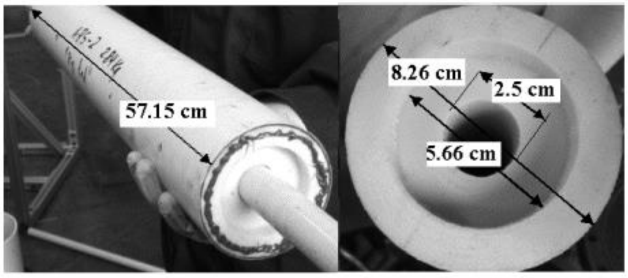

Figure 12 – ABS Fuel grain dimensions

After 40 successful static fire tests of traditionally cast HTPB and FDM ABS, burn profiles were determined and reviewed for similarity. Figure 13 plots the longitudinal mean regression rate predictions and measurements for both HTPB and ABS against the mean oxidizer mass flux.

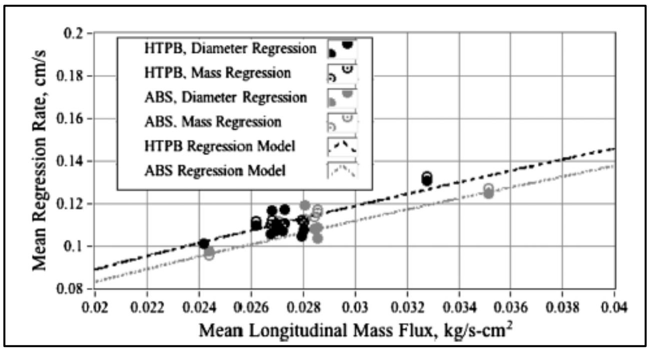

Figure 13 – Predicted and measured linear regression for HTPB and ABS fuel grains

The corresponding fuel burn rates are 0.082 kg/s (HTPB) and 0.086 kg/s (ABS), calculated by dividing the total consumed fuel by the total burn duration. The mean oxidizer mass flows for HTPB and ABS burns are 0.304 kg/s and 302 kg/s respectively. Both experimental and analytical calculations agree in predicting slightly higher linear regression rate for HTPB compared to ABS, however, considering the lower density in HTPB, the solid fuel mass flow rate at a given oxidizer mass flux is nearly identical.

3.2. High Regression Rate for Fuel Grains with Helical Ports

Whitmore and Utah State University coworkers went a step further with their fuel grain additive manufacturing studies. In 2015, experiments were performed using ABS and HTPB fuel grain hybrid rockets but testing for criticality and impacts of using helical ports, more consistently manufactured using FDM processes.

Helical pipe flows are well known to have the effect of increasing the local skin friction coefficient. Helical flows also introduce centrifugal component into the flow field. The experiment performed by Whitmore is preceded by analytical predictions that explore surface skin friction effects using the models developed by Mishra and Gupta. Mishra and Gupta were engineers who investigated a wide range of coil geometries for both laminar and turbulent flow conditions. Combining existing Marxman theory and analytical Mishra-Gupta models, the results of experimental findings were assessed.

The test consisted of four cases: one control ABS fuel grain of cylindrical combustion port and three helical ports with varying helix geometries. Gaseous oxygen was used for oxidizer. Measurements recorded were thrust, chamber pressure, ignitor case temperature, inlet and throat pressures, total impulse, exhaust temperatures, specific impulse, mass flow rate, and propellant regression rates, not unlike the 2013 experiments. Real-time thrust motor mass measurements were recorded. Each grain was burned multiple times, with the control grain burning from 1 through 4 second durations. The helical port configurations were burned between 2 and 3 seconds. A total of 16 firings were performed.

Figure 14 compares the thrust and chamber pressure profiles obtained from the testing. Figure 15 presents mass flow time history plots with mass flow rate. Figure 16 plots oxidizer-to-fuel ratio as a function of burn time for each tested fuel grain.

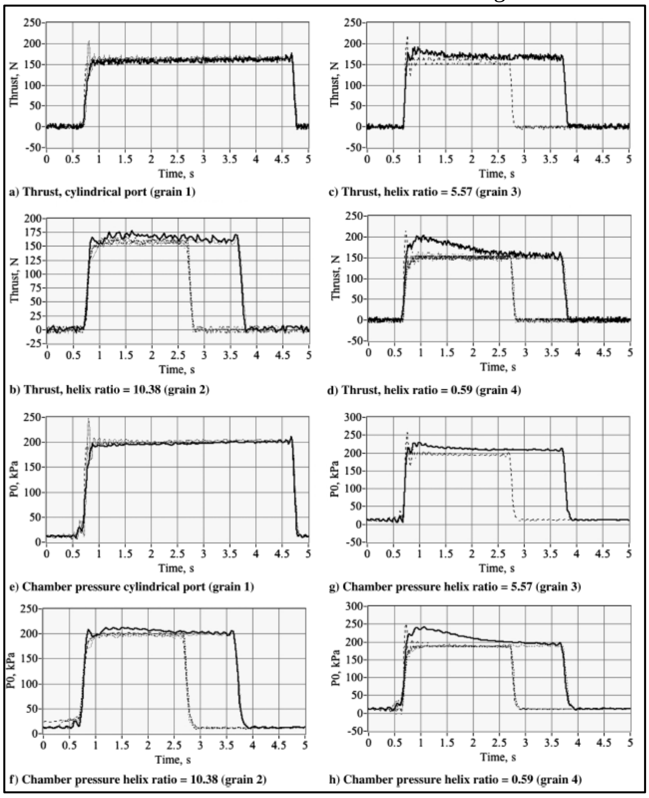

Figure 14 – GOX-ABS tests; Thrust and chamber pressure time histories

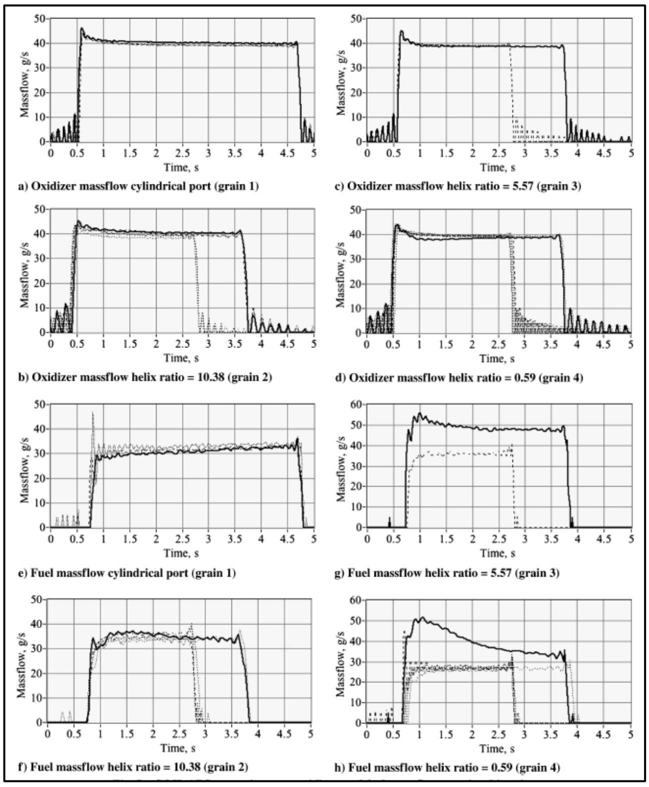

Figure 15 – GOX-ABS tests; Oxidizer, and fuel mass flow rate time histories.

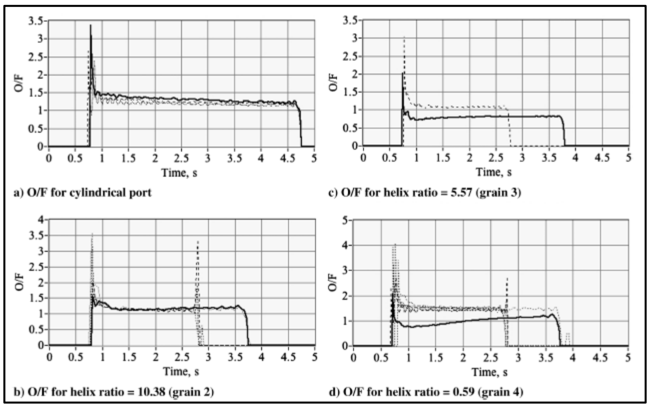

Figure 16 – GOX-ABS tests; Variation in O/F with burn time.

Figure 17 is a result of multiple calculations of mean regression rate profiles and measured parameters during the experiment. The plotted symbols represent the regression rate data calculated from the test burns and the plotted lines represent the predicted regression rate calculated using modified Marxman model. Figure 18 shows post-test fuel grain cross-sections.

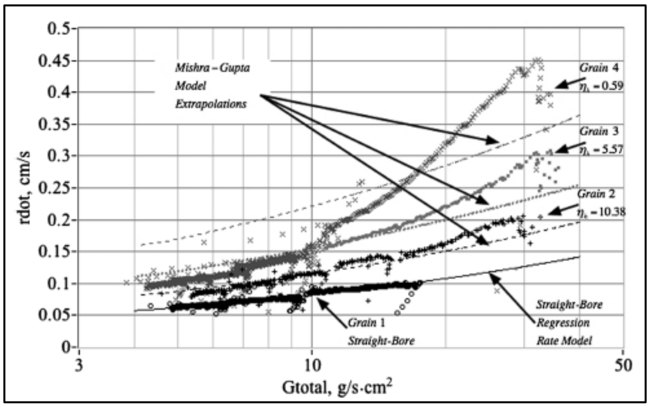

Figure 17 – GOX-ABS regression rate for straight-bore and helical grains

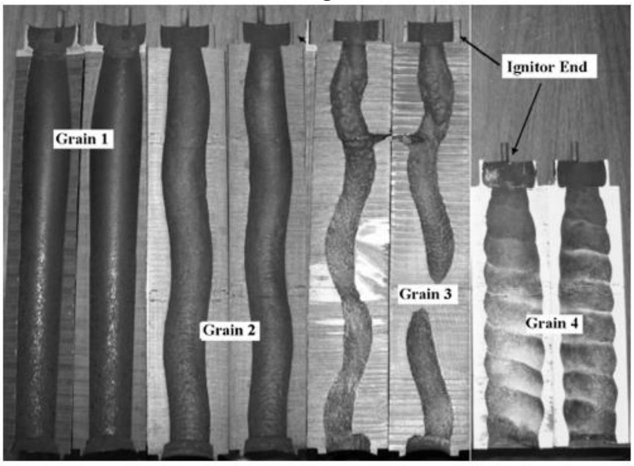

Figure 18 – Post-Test fuel grain cross sections

As shown by the data, the radial wall-blowing due to fuel pyrolysis is suppressed by centrifugal forces introduced by the helical flow and compresses the flame zone layer closer to the port walls. Convective heat is significantly increased and contributes directly to the observed regression rate increase in the helical fuel grains.

5. Conclusion

Since ABS can easily be manufactured in an almost infinite variety of shapes using additive processes, there exists the potential to further optimize higher regression rates for fuel grains. One example is the design of a high regression rate port structure and addition of fuel ports that minimizes the oxidizer-to-fuel ratio shift. Based on the presented results from Utah State University, both the increase in local skin friction coefficient and radial blowing suppression must be considered when developing an "optimal" port design.

A suggested follow-up research activity is to reproduce the presented test matrix using a traditional hybrid propellants other than HTPB. The simplest helices have been shown to produce significant effects and combined with multiple port structures would result in some interesting findings. [8] The implementation of swirl effects that is proven to increase regression rate [9] can also be explored in a configuration where both multiple-helical port fuel grains can exist. Metal oxidizers manufactured within the fuel grain is another alternative to increase fuel grain. [10] Fused deposition manufacturing methods have opened the way for an exciting future in hybrid rocket engine optimization.

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