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Application of Three Thrust Levels in a Single Fuel Grain for a Hybrid Motor

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This study presents the development of a three-thrust-level hybrid rocket motor, employing both geometric and chemical enhancements within a single fuel grain to optimize performance across distinct flight phases. The initial high-thrust phase is achieved by implementing a helical-port structure, which extends the oxidizer flow path and induces centrifugal turbulence, significantly increasing the fuel regression rate and flow rate. During the second, cruise phase, thrust is moderated due to helical structure breach and the formation of a straight cylindrical port. In the final phase, a high-thrust output is achieved by incorporating 5% expandable graphite (EG) into the fuel, leveraging EG's high thermal conductivity to accelerate regression. Static firing tests validate this multi-phase thrust profile, revealing superior regression rates and fuel efficiency over traditional designs and demonstrating the efficacy of combining geometric and compositional strategies in hybrid propulsion systems.

Contents

Introduction

Hybrid rocket motors utilize a configuration in which the fuel and oxidizer exist in two different phases. The oxidizer, which may be gaseous or liquid, flows through the port of a solid fuel grain. Hybrid motors are characterized by inherent safety, simplicity, and controllable thrust, distinguishing them from both solid and liquid rocket motors. Their safety and controllability arise from the ability to start, stop, intensify, or reduce operation via oxidizer flow regulation using a valve. Additionally, the fuel, typically composed of non-explosive polymers, contributes to their safety.

However, a primary limitation of hybrid rocket motors is the low regression rate of the fuel. The separation of fuel and oxidizer phases results in a diffusion-limited combustion process, as combustion depends on the rate at which the oxidizer diffuses to the fuel surface. Consequently, heat is transferred more slowly to the fuel surface, resulting in a slower gasification process of the fuel, leading to a slower combustion process and reduced thrust.

Two primary strategies have been proposed to address the low regression rate: optimizing fuel grain geometry and enhancing the chemical composition of the fuel. The geometric approach focuses on shaping the grain to increase the wetted surface area exposed during combustion, while preserving high oxidizer mass flux. The second approach involves improving the fuel's chemical properties. This study combines both the geometric approach and the enhanced burning rate approach via specific chemical composition, demonstrating the effect by developing a three thrust-level fuel grain.

The static firing tests in this investigation utilized gaseous oxygen (GOX) as the oxidizer and a single-helical-port polyester grain as the fuel.

The primary objective of the study is to design a single fuel grain capable of delivering:

- **Stage 1:** High thrust for the launch phase.
- **Stage 2:** Reduced thrust for the cruise phase.
- **Stage 3:** Increased thrust for the end-of-flight phase.

The first stage will be achieved through the geometric approach by incorporating a helical port into the grain design. The second stage, characterized by lower thrust, will naturally occur after the breach of the helix, transitioning to a straight cylindrical port. The third stage of increased thrust will be accomplished by adding Expandable Graphite (EG) particles to the fuel composition which increase the fuel regression rate.

Helical Port

Two key parameters contribute to the increased fuel consumption rate and thrust in a helical-shaped port: (1) the elongation of the oxidizer's internal flow path, and (2) the generation of turbulent centrifugal flow, which reduces the boundary layer thickness. This results in a shorter flame distance and enhances heat transfer to the fuel surface, thereby increasing the local regression rate.

Lee et al. (2007) [1], with their goal to extend the positive effects of swirl injection (typically concentrated at the grain's head) throughout the entire length of the fuel grain, demonstrated an increase of up to 185% in regression rate by combining a moderate injection swirl with a moderate helix. Whitmore et al. (2015) [2] developed a model to analyze the effects of helical fuel ports on the hybrid fuel regression rate and concluded that the increased regression rate was primarily due to helix-induced skin friction. Experimentally they demonstrated a 200%–400% increase in the fuel regression rate, depending on the helical structure. However, a discrepancy between analytical predictions and experimental results led to the conclusion that the rotational flow velocity within the helical fuel port, which thins the surface boundary layer, may contribute significantly to the regression rate increase, equivalent to the skin friction effect. Later, in 2017, Whitmore and Walker [3] revised the model and showed that approximately 75% of the regression rate amplification was due to the increase in skin friction from helical rotation, with the remaining amplification attributed to the centrifugal flow suppression of radial wall blowing. Their model was validated by comparison with experimental data, yielding a small mean error of 7.5%. Dinisman et al. (2023) [4] in their static firing tests observed a helical port with a large helix loop diameter equal to the helix's pitch, resulting in an oxidizer that changes its direction tangent to the helical shape. An increase of up to 250% in regression rate compared to cylindrical port was reported.

Expandable Graphite (EG)

Expandable Graphite (EG) is an intercalated form of graphite, typically supplied as flakes in a typical size of 100–500 μm, in which guest molecules are inserted between the carbon crystal layers. EG exhibits high thermal conductivity, corrosion resistance, softness, and compression resilience. At elevated temperatures, typically around 180°C, EG elongates and expands into strings that are an order of magnitude longer than the original particle size.

Elanjickal and Gany (2020) [5] hypothesized that incorporating EG flakes into hybrid fuel grains could enhance the regression rate by improving heat transfer to the fuel. As combustion occurs and temperatures rise within the motor, the embedded EG flakes elongate and protrude from the burning surface. These exposed flakes are heated by the flame, transferring heat to the deeper layers of the fuel grain via conduction, leading to increased fuel consumption. Since EG's thermal conductivity is several orders of magnitude higher than that of polymers, even a small percentage of EG added to the fuel can significantly improve the regression rate. Their static firing tests demonstrated a 100% increase in regression rate for polyester fuel and a 50% increase for paraffin fuel when 5% EG was incorporated into the mixture.

Muller and Gany (2020, 2022, 2023) [6-8] provided direct visual evidence of the formation and protrusion of elongated EG strings from fuel surfaces exposed to flame using high-speed photography.

Dinisman et al. (2023) [4] investigated the effect of a 5% EG additive in a polyester single-helical-port grain. Their research revealed a 300% increase in regression rate compared to a cylindrical polyester grain without EG, while a 250% increase was observed in the polyester helical-port grain without EG.

Experimental setup and test procedure

Casting

For the two inner stages of the fuel grains (helical port burn and cylindrical cruise burn), Polyester H-7/M was used, combined with 1% (of the polyester mass) of hardener methyl ethyl ketone peroxide. The outer cylinder was composed of Polyester H-7/M mixed with 5% by mass of 100μm flakes of EG-type ES 100 C10, along with 1% by mass of the same hardener.

The materials were cast into 3D-printed ABS molds, specifically designed to produce the required burn characteristics. After solidification, the grains were immersed in a heated acetone bath (40°C) to dissolve the ABS mold. A thin ABS layer (0.8 mm) separating the two materials remained intact, as the acetone could not penetrate this layer, which subsequently served as an effective adhesive interface. Finally, the top and bottom surfaces of the grains were polished to fit the experimental setup. At the end of the process the grain was weighed. The fuel casting process is presented in Fig. 1.

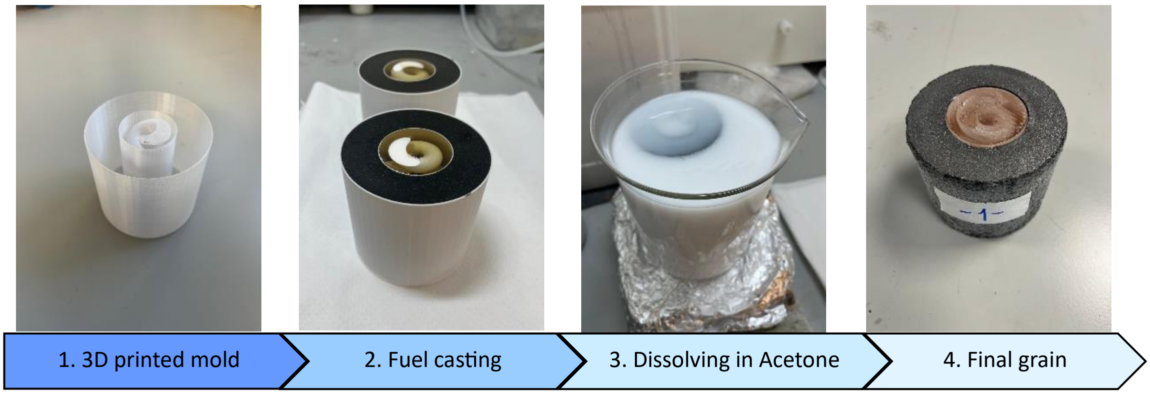

Fig. 1: Fuel Grain Casting Process

Experimental setup

The static firing system is depicted in Fig. 2. The fuel grain serves both as the fuel and the combustion chamber casing. The forward end of the grain was connected to the oxygen injection section, whereas the aft end was attached to a mixing chamber, which was further linked to a converging nozzle with a 6.25 mm throat diameter. Ignition was initiated by an electric spark, triggered during a brief (0.1 second) injection of ethylene gas into the oxygen flow.

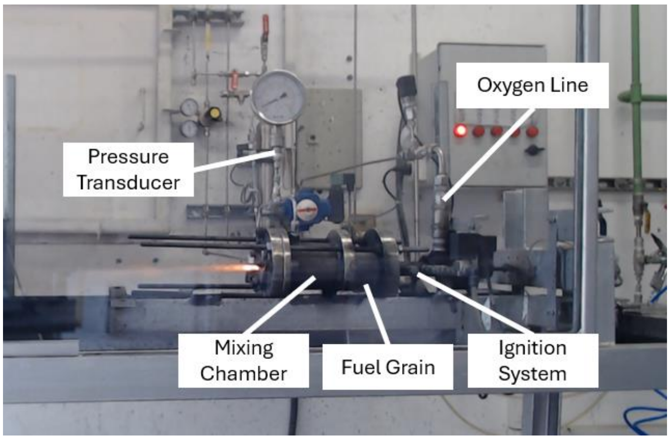

Fig. 2: The Test System during static firing

The dimensions of the fuel grain were as follows:
For the helix: length $L = 70\ mm$, helix port initial diameter $d_i = 10\ mm$, helix loop diameter $D_{helix} = 30\ mm$, helical pitch $P = 20\ mm$.
The second stage initiates at the breach of the helix, approximately at a diameter of 34 mm, and ends at the onset of the outer cylindrical stage with 5% EG. This transition from pure polyester to polyester with EG corresponds to a diameter of $D_{EG} = 38\ mm$.
Outer diameter of the grain $D_o = 78\ mm$.
A scheme of the grain is shown in Fig. 3.

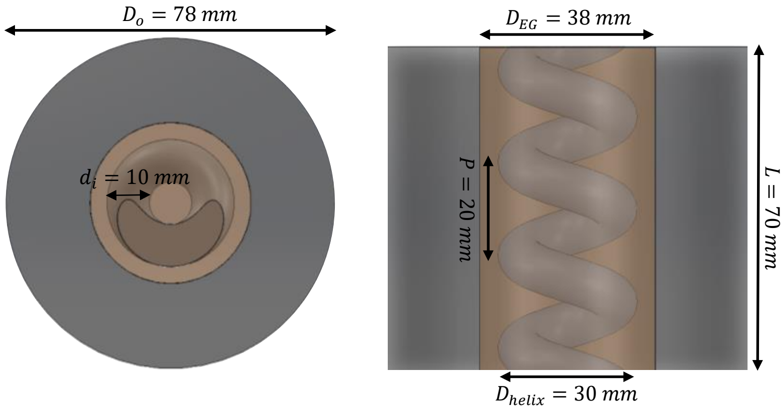

Fig. 3: Fuel Grain Scheme

During system operation, instantaneous thrust, pressure, and oxygen flow rate were continuously recorded and monitored. The average fuel flow rate was determined by measuring the mass of the fuel grain before and after each test and dividing the difference by the burn time. This value was then used to calculate the oxidizer-to-fuel (O/F) ratio to ensure optimal operating conditions. The experiments were streamed and documented using a high-definition video camera.

A dedicated software program was employed to manage and control the experiment. For the first 8 seconds following ignition, the oxygen flow rate was set to 14 g/s. Subsequently, the flow rate was reduced to 5 g/s for the next 4 seconds, and during the final stage, which lasted 5 seconds, the oxygen flow rate was increased to 8.7 g/s.

Results

1st Sub-Experiment: Isolating Helical Port Effect

Prior to the main experiment, two preliminary sub-experiments were conducted. In the first sub-experiment, a polyester grain with a helical port, but without graphite, was tested to isolate the contribution of the helical shape to the regression rate during the first stage (Fig. 4). This experiment was carried out with a constant oxygen flow rate of 10.1 g/s and lasted for 12 seconds.

The results are shown in Fig.5. The measured thrust prior to the breach of the helix (21.3 N) was 1.57 times higher than after the breach (13.5 N). The breach, characterized by a transition from a large burning area to a smaller one, can be identified by the drop in thrust. As previously discussed, the enhancement in regression rate—and consequently in thrust—results from the increased burning surface area with a proper $\dot{m}_{ox}$ maintained, combined with improved mixing facilitated by the helical port design.

Fig. 4: 1^{st} Sub-Experiment Fuel Grain

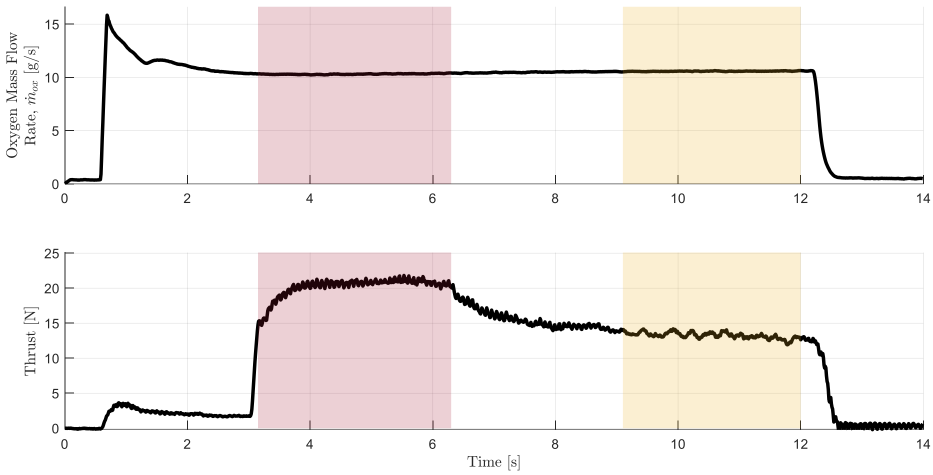

Fig. 5: Results of The First Sub-Experiment: Polyester Grain With a Helical Port

2^{nd} Sub-Experiment: Isolating Expandable Graphite Effect

The second sub-experiment was performed to isolate the effect of Expandable Graphite (EG) on the regression rate. In this experiment, a two-layer straight cylindrical port was tested. The inner layer consisted of plain polyester, while the outer layer was composed of polyester enriched with 5% EG (Fig. 6). The experiment was conducted with a constant oxygen flow rate of 9.4 g/s and lasted for 20 seconds.

The results are shown in Fig. 7, indicating two thrust levels. The average measured thrust at the onset of the experiment, utilizing plain polyester, was 12.8 N. In contrast, the thrust measurements at the conclusion of the experiment, which involved polyester incorporated with 5% expandable graphite (EG), yielded a value of 23.7 N. This demonstrates a 1.85-fold thrust enhancement.

After approximately 10 seconds, the EG close to the burning surface begins to elongate and protrude through the surface to the hot gas environment, thereby improving thermal conduction into the fuel, increasing the regression rate. This transition is gradual, as the port is not fully symmetrical; once the flame penetrates further into the fuel, the ABS and pure polyester layers are fully removed and combustion involves only polyester with 5% EG, resulting in a constant thrust curve with high magnitude.

Fig. 6: 2^{nd} Sub-Experiment Fuel Grain (inner layer plain polyester, outer layer polyester with 5% EG)

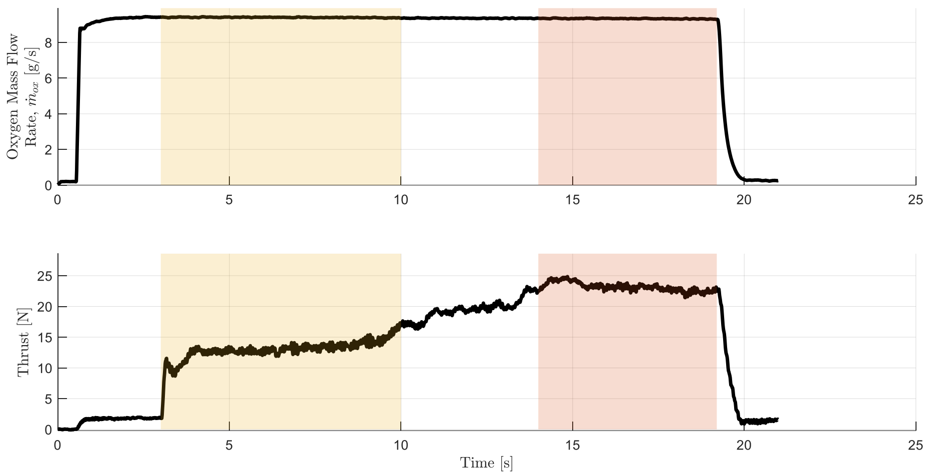

Fig. 7: Results of the Second Sub-Experiment: Cylindrical Port Grain with Inner Layer of Polyester and Outer Layer of Polyester With 5% EG

Main Experiment: Combination of The Two Techniques

Following the completion of the two sub-experiments, the main experiment was conducted. This experiment integrated the two regression rate enhancement techniques and successfully demonstrated a three-stage thrust profile, as intended. In the first burning phase, a helical port was utilized until a breach occurred, followed by a cylindrical polyester burn, and concluding with the burning of a section of a cylindrical polyester containing 5% expandable graphite (EG). The fuel grain consisting of the three different sections, is displayed in Fig. 8. The results, shown in Fig. 9, indicate that the first stage produced high thrust, attributed to the helical port effect on increasing the regression rate and overall fuel consumption rate. The breach, marked by a sharp drop in thrust, occurred at 11.3 seconds into the experiment. The average thrust in the first stage was 42.5 N. It was followed by the second, cruise stage, where the average thrust was 12.7 N, and concluded with high thrust at the final stage. During the transition from the second to the third stage, a thrust increase of 115% was observed, rising from 12.7 N to 27.4 N. This enhancement in thrust can be attributed to two primary factors: the transition to combustion of EG-containing fuel and the increase in oxygen flow rate from 5 g/s to 8.7 g/s. Given that graphite has a higher thermal conductivity, it leads to an elevated combustion rate, necessitating a corresponding increase in oxygen flow to sustain optimal oxygen to fuel (O/F) ratio, implying optimal energetic performance. A similar adjustment was made in the first stage, where the flow rate was set at 14 g/s.

Fig. 8: Main Experiment Fuel Grain

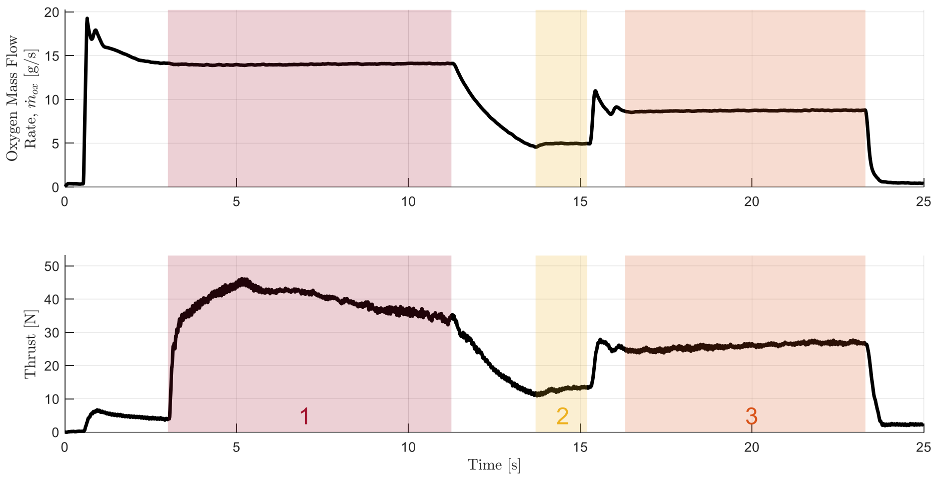

Fig. 9: Three-Stages Experiment: Polyester Helical Port Until Breach, Polyester Cylindrical Post-Breach Burning, and Polyester With 5% EG

Theoretical calculation of the characteristic velocity (C*), a measure of the energetic performance of the propellant, was estimated with the aid of NASA CEA thermochemical code [9], assuming chemical equilibrium in the combustion chamber at constant pressure of 10 atm.

Fig.10 illustrates the characteristic velocity as a function of the O/F ratio for both plain polyester and polyester blended with 5% expandable graphite (EG). As shown, there is practically no difference between plain polyester and graphite-containing polyester; the optimal O/F ratio for both materials is 1.3, which was targeted in the experimental setup by adjusting the oxidizer mass flow rate.

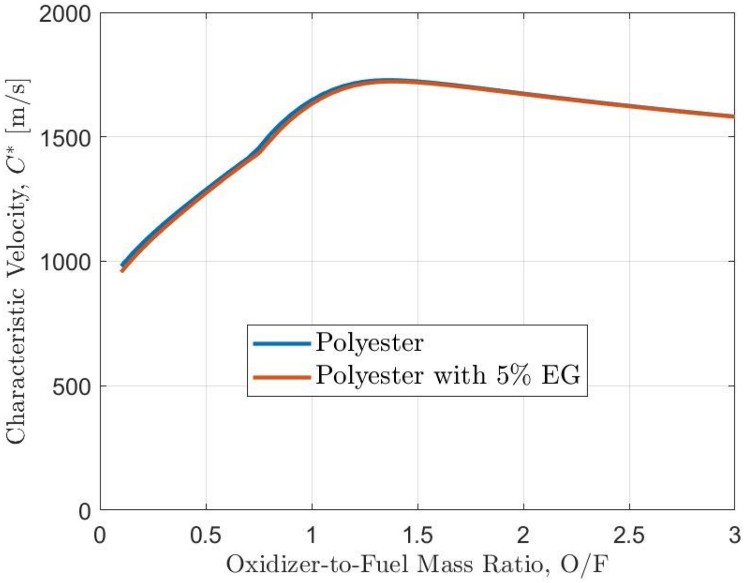

Fig. 10: Theoretical C as a Function of O/F Ratio For Polyester and Polyester With 5% EG Burning with Oxygen*

While the change in oxygen flow rate significantly contributes to the increase in thrust, it is not the sole factor at play.

To explore this further, we can utilize the thrust equation:

$$F = \left(\dot{m}_{ox} + \dot{m}_f\right) \cdot u_e \quad (1)$$

where $\dot{m}_{ox}$ and $\dot{m}_f$ represent the mass flux of oxygen and fuel, respectively, and u_e denotes the exhaust velocity from the engine. In the third stage, the oxygen flow rate was 1.77 times higher than in the second stage; however, the thrust observed was 2.15 times greater. This suggests that an additional contributing factor is the incorporation of expandable graphite (EG), which enhances heat conductivity leading to an increased regression rate beyond the effect of the increased oxygen mass flux.

It is also important to note that the factor of 1.77 for $\dot{m}_{ox}$ does not translate directly into a 1.77-fold increase in thrust, as the mass flux of fuel ($\dot{m}_f$) must also be considered. Therefore, we conclude that the contribution of EG to the overall thrust enhancement is likely even more significant than indicated by the changes in oxygen flow alone.

Conclusions:

This study aimed at investigating an actual possibility to produce three thrust levels during the operation of a hybrid motor employing a single solid fuel grain. The study demonstrated via static firing tests that a combination of a fuel grain having a helical port (special structural shape) with an outer layer of improved chemical composition, can accomplish this requirement. The helical shape of the fuel port (plain polyester) causes a substantial increase in the overall fuel consumption, hence producing a high thrust level. The following occurrence of the breach of the helical shape results in the formation of a cylindrical port, producing lower fuel consumption rate and, hence, lower thrust. Transition to an outer layer where the polyester fuel is enriched with 5% EG particles demonstrates a noticeably higher fuel regression rate than the previous plain polyester layer, resulting in a remarkably higher thrust.

Acknowledgement

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References

[1] Lee, C., Na, Y., Lee, J.-W., and Byun, Y.-H., Effect of Induced Swirl Flow on Regression Rate of Hybrid Rocket Fuel by Helical Grain Configuration, *Aerospace Sci. Technol*., vol. 11, no. 1, pp. 68–76, 2007. DOI: 10.1016/j.ast.2006.07.006

[2] Whitmore, S.A., Walker, S.D., Merkley, D.P., and Sobbi, M., High Regression Rate Hybrid Rocket Fuel Grains with Helical Port Structures, *J. Propul. Power*, vol. 31, no. 6, pp. 1727–1738, 2015. DOI: 10.2514/1.b35615

[3] Whitmore, S.A. and Walker, S.D., Engineering Model for Hybrid Fuel Regression Rate Amplification Using Helical Ports, *J. Propul. Power*, vol. 33, no. 2, pp. 398–407, 2017. DOI: 10.2514/1.B36208

[4] Dinisman, S., Eisen, N.E., and Gany, A., “Enhancing Hybrid Motor Thrust by a Helical-Port Fuel Grain”, *International Journal of Energetic Materials and Chemical Propulsion*, vol. 23, no. 1, pp. 69-84, 2023. DOI: 10.1615/IntJEnergeticMaterialsChemProp.2023049385

[5] Elanjickal, S. and Gany, A., Enhancement of the Fuel Regression Rate in Hybrid Propulsion by Expandable Graphite Additive, *Combust. Sci. Technol*., vol. 192, no. 7, pp. 1253–1273, 2020. DOI: 10.1080/00102202.2020.1748017

[6] Muller, G.T. and Gany, A., Burning Phenomena of a Polymeric Fuel Containing Expandable Graphite, *Propellants Explos. Pyrotech*., vol. 45, no. 11, pp. 1764–1768, 2020. DOI: 10.1002/prep.202000138

[7] Muller, G.T. and Gany, A., Expandable Graphite Effect on Solid Fuel and Propellant Combustion, *Fire Phys. Chem*., vol. 2, no. 1, pp. 72–75, 2022. DOI: 10.1016/j.fpc.2021.12.001

[8] Muller, G.T. and Gany, A., Increasing Burning Rate and Motor Thrust by Expandable Graphite Additives, *J. Propul. Power*, vol. 39, no. 5, pp. 709–717, 2023. DOI: 10.2514/1.B39126

[9] Gordon, S., and McBride, B., “CEA, Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications,” NASA Lewis Research Center, NASA Reference Publ. 1311, Cleveland, OH, 1994.