

Hybrid Rocket Propellant Grains: A Review

Nishad Bhavsar¹, Paarth Saxena^{1,*}, Prasad Sawant¹, Maitreyee Birajdar¹, Pandi Siddharth²

Abstract

The go-to-rocket propulsion system is either solid rocket motor or liquid rocket engine, but both have their own drawbacks like solid rocket motors cannot be throttled or stopped and started again or the construction of liquid propulsion systems is quite complex, with difficulty in storage and major safety issues. A hybrid rocket propulsion system uses either fuel or oxidizer in solid form and the other in liquid and has a lot of advantages over the conventional propulsion systems. As hybrid rockets usually provide a few advantages over solid and liquid propulsion rockets, like hybrid rocket system can be turned off and on again, it can also be throttled easily by controlling the flow of the liquid component of the propellant. This paper presents a thorough review of hybrid rocket propellant grains, encompassing their historical development, fundamental principles, design considerations, performance characteristics, and recent advancements.

Keywords: Propellants, grain geometry, hybrid rocket, throttle, propellant grain

INTRODUCTION

The hybrid rocket propulsion system combines both solid and liquid propulsion systems, one part of the propellant is solid and the other part is liquid, usually the solid part is the fuel of the rocket and is called the propellant grain. This system provides a lot of distinct advantages over the traditional propulsion systems that are in use, they provide a higher specific impulse (I_{sp}) than solid propulsion systems. As such the liquid propulsion system are prone to leaks and safety risks, they are also very complex in nature. In comparison, the hybrid propulsion system provides much higher safety while maintaining a simpler design and construction.

One of the key features of hybrid rocket engines is the ability to tailor the grain configuration to meet specific mission requirements. The grain design can influence combustion stability, thrust profile, and overall engine performance. Various grain geometries, such as cylindrical, star, or multi-port configurations, can be employed to optimize combustion efficiency and enhance thrust characteristics.

Hybrid rockets are also quite compatible with a variety of oxidizers, like oxygen, nitrous oxide, hydrogen peroxide which can be used to achieve specific performance depending on the mission parameters and availability of the oxidizers.

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CONSTRUCTIVE DESIGN

Propellants, the driving force of the hybrid rockets can have a composition that is fairly complex, and may contain oxidizers of various mesh sizes, polymer binder, and even metals such as aluminum or magnesium. Curing agents, phase stabilizers, and solvents may be other additives included in small percentages as shown in Figure 1. They are all shaped into similar geometric shapes called the propellant grain, their outer shape is mostly a cylinder.

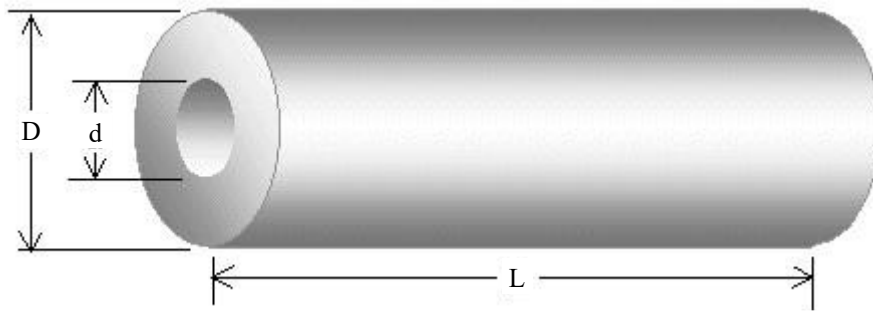


Figure 1. Cylindrical propellant.

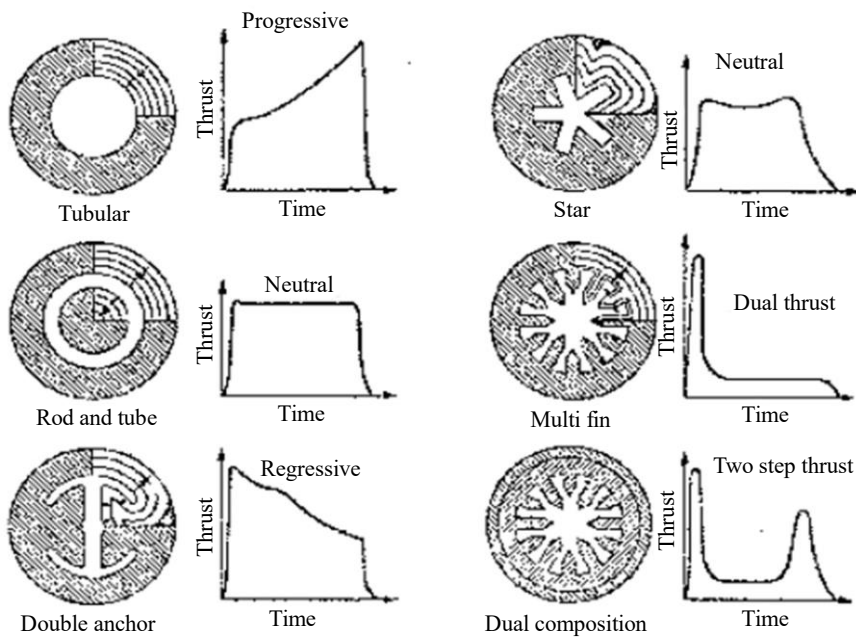


Figure 2. Conventional geometries.

These grains have a port or a hollow section in the middle that extends throughout the length of the propellant grain, its shape can be changed to any desired one and it affects the performance of the rocket significantly. There are mainly six conventionally used geometries as shown in Figure 2.

As can be seen from Figure 2, the shape of the grain significantly affects the burning of the propellant and the thrust produced over the time of the burning of the rocket motor, it is found out that higher the surface area for burning higher is the rate of burning, producing a higher amount of thrust.

The amount of thrust is also affected by the shape of the grain as the burning pattern is normal to the shape of the grain initially. The thrust it generates is directly proportional to the burning area at any particular instant in time.

The burning pattern is also referred to as the web pattern and it shows how the regression of the grain progresses and the higher the surface area of the web pattern the higher will be the regression rate, and the thrust produced as shown in Figure 3. If the web pattern is constant, the rocket motor will produce a constant amount of thrust and have a stable regression rate which is desirable for most rocket operations.

Shown in Figure 3 is the web pattern for the star shape geometry for the propellant grain. It has a quite consistent burning web and will produce a constant thrust as the surface area of burning is mostly constant. Of all the conventional geometries this is the most efficient and producing a constant thrust.

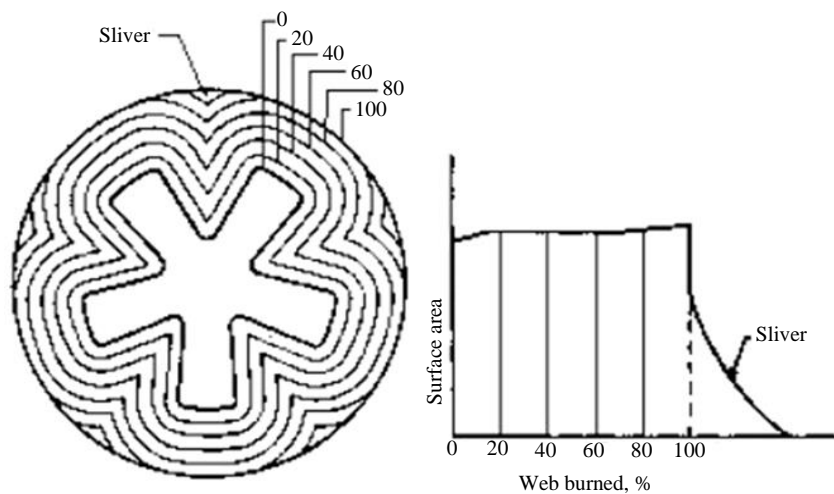


Figure 3. Burning pattern of grain.

This web pattern can easily be compared by calculating the web ratio for the distinct geometries. It is calculated as the ratio of the web thickness of the propellant grain to the outer radius of the grain, it can be found using the following equation:

$$W_f = \frac{D-d}{D} = \frac{2 r b_0}{D}$$

where b is the burn time for the rocket. To obtain maximum burn time we need to maximize the web ratio for the propellant grain. The port to throat ratio is needed to maintain the chamber pressure. The ratio is given by flow channel cross-sectional area to the nozzle throat cross-sectional area.

$$\frac{A_p}{A_t} = \frac{\pi D^2(1-V_1)}{4 A_T}$$

Usually, the port to throat ratio is preferred as 2 to 3 and L/D ratio as 6 because it is found to produce more effective burning while maintaining the chamber pressure optimum. Studies have shown that the regression rate decreases with increases in port diameter.

Larger the L/D , higher the amount of CO_2 produced, which means a higher combustion efficiency and regression rate. As the L/D increased and mass flow rate of the fuel increased, the regression rate and the combustion efficiency both were increased.

OBJECTIVE

Our review focuses on comparing the findings and research papers on different propellant grains, their geometries, the combination of various fuels, oxidizers, and additives and various parameters of the grain which describes us their combustion efficiency like regression rate, burning time, overall thrust produced. Our review encompasses the notion of selection of the most compatible propellant grain geometry to our requirements.

WORKING

In recent years, there has been more research in this type of propulsion and a new manufacturing technique is being used to make the propellant grains which is called 3D printing. The printer melts the material and forms layer upon layer till it forms the complete 3D solid model. The material used in the printing is called ABS (acrylonitrile butadiene styrene) which is a bioplastic with high reactivity and has proved to be compatible with good combustion ability, many studies are using it to test hybrid rockets.

In a 2023 study by Funami and Takano [1], a swirl shape geometry was made and was tested, it was then compared to a pervious experiment they had conducted with a star geometry, the model was 3D printed using ABS, nitrous oxide for oxidizer, while oxygen was used as an igniter.

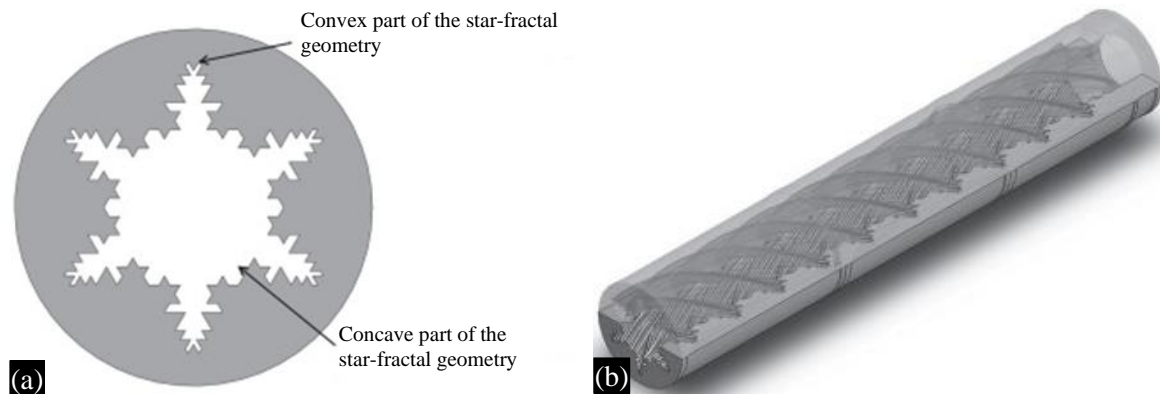


Figure 4. (a) Cross-section of the grain with a star-fractal swirl port, (b) grain with a star-fractal swirl port: an injector is inserted at the right end of the grain. Upper half portion is translucent for visibility.

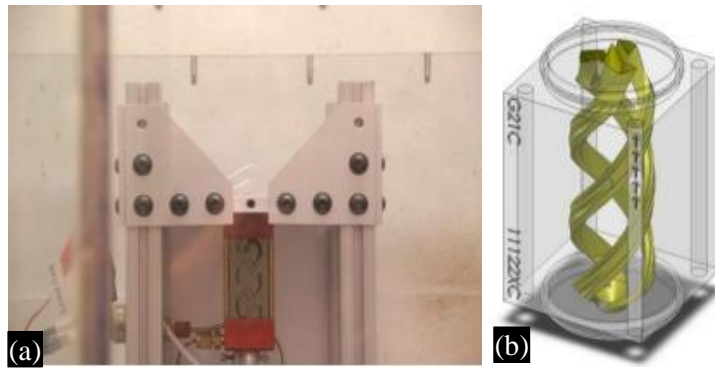


Figure 5. (a) A RP (rocket propellant) fuel grain ready for testing, (b) Solid model of a 3-port helix test grain.

They found out that the specific impulse, thrust and regression rate were significantly increased as shown in Figure 4. This was because the area of burning increased with a little swirl that increases the flow velocity vector.

There has been a lot of research in the use of 3D printing from the production of propellant grains, it is because 3D printing allows us to readily print complex geometries for the propellant grain with the need to specialized equipment or the need for developing new molds or new manufacturing techniques. 3D printing allows us to get the grains to be printed in a shorter amount of time. It also reduces the overall tooling costs as no other equipment is required, it also reduces the experimentation time as these grains can be produced faster as they do not require expensive and time-consuming construction of molds for different geometries.

It is not just that 3D printing is being researched, some research is focused on using additives and other fuel for the combustion in addition to the 3D printing material used to produce the propellant grain. A RP fuel grain ready for testing is presented in Figure 5.

A research paper by Jacob A. Bresler and Benveniste Natan [2] published in 2019, reported their experiments with a 3D printed ABS casing and paraffin wax [2]. The control was established using a pure ABS propellant grain, it is known that liquid propellant has much higher regression rate so when paraffin is used in combination the ABS, the wax melts during combustion and increases the regression rate and this type of fuel whose outside layer liquifies and then burns are called as liquefying fuels. In the experiment a Raise 3D N2 plus with a 0.4 mm (about 0.02 in) extruder nozzle was used to print the propellant grains using ABS as shown in Figure 6.

The ABS skeleton was printed in segments and then joined as shown in Figure 6, and the paraffin was heated and then poured into the skeleton and let to rest in a refrigerator for 24 hours to maintain uniformity and to maintain a constant temperature to minimize errors while testing, the test was carried out using oxygen as the oxidizer and the skeletons were made using different angles between the body and the flow of the oxidizer.

It was found out that the regression rate of the paraffin was significantly higher than the pure ABS as shown in Figure 7, it was also found out that the angle between the cone and the flow of the oxidizer also significantly affected the regression rate higher was the angle, higher was the regression rate. It was found that with paraffin the min increase in the regression rate was about 0.7 mm/s. The highest regression rate was achieved by the cone pointing in the opposite direction as the flow. The results can be seen in Figure 7.

In a paper by Yu et al [3], the packing density or the amount of infill of the 3D print was changed for standard grains the infill is at 100%, the packing density refers to how densely the grain is packed according to the geometry for example a grain with tubular geometry and 50% packing density will have about 50% of the volume hollow as channels, this can be seen by the Figure 8.

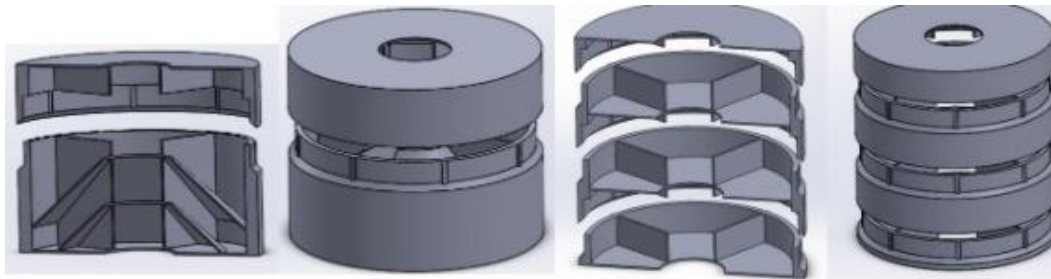


Figure 6. ABS (acrylonitrile butadiene styrene) skeleton.

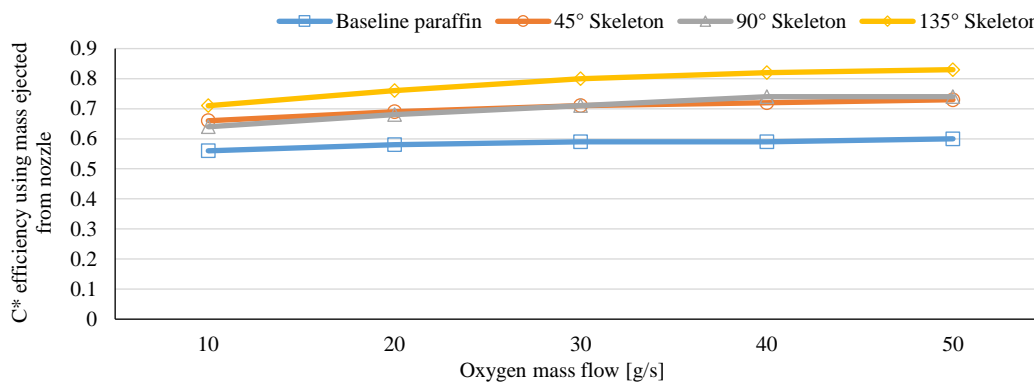


Figure 7. Regression rate in opposite direction.

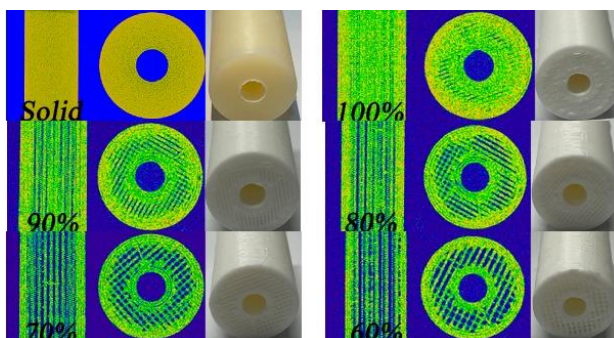


Figure 8. Tubular geometry.

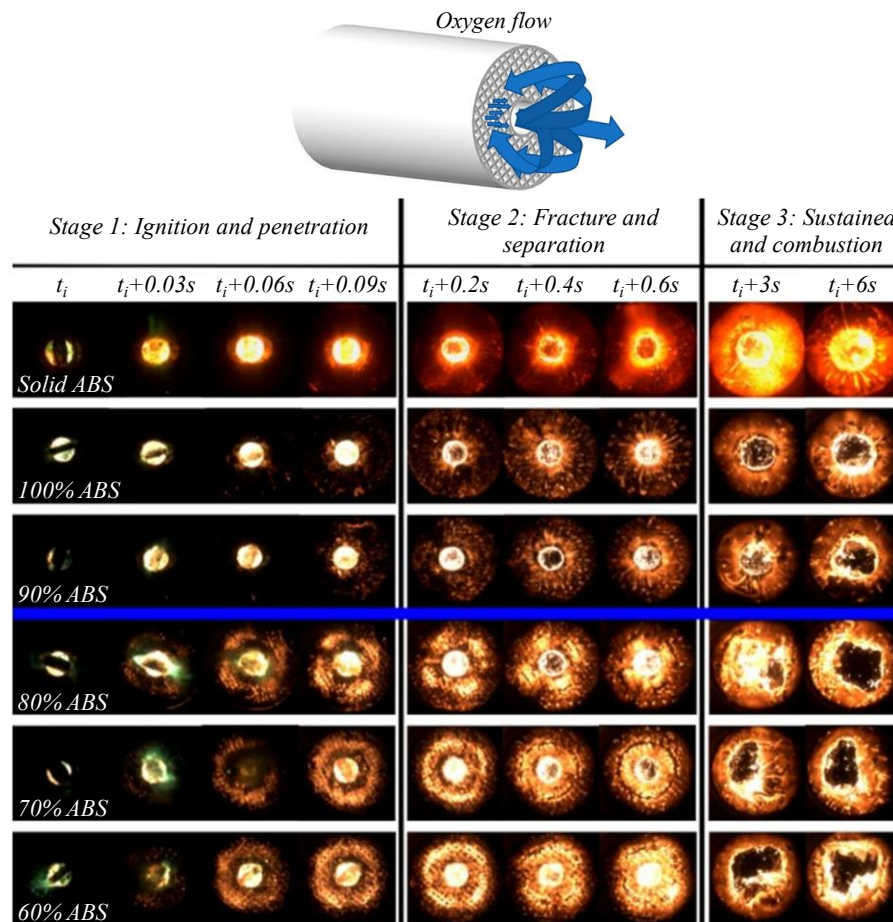


Figure 9. Thrust production by the grain.

There were numerous grains with different packing densities were produced and then tested using oxygen as the oxidizer, the flow rate was maintained at a constant value and the grains were identical in all aspects but the packing density or the porosity of the grain.

It was observed in the experiment that porosity increases and with the reduction in packing density the regression rate increases with it. The reduction in the packing density did increase the surface area available for the combustion but this led to another problem that reduced the overall performance of the propellant grain. The extra channels for the oxidizer to flow led to the formation of back flow which reduced the thrust produced by the grain, and it can be seen in Figure 9.

There are a lot of research studies being carried out on hybrid rockets and their propellant grains, and have resulted in significant advancements in hybrid systems, there has been research and a preference to using ecofriendly oxidizers like N_2O , and there has been significant successes in testing and the use of paraffin wax based propellant is also seen significant development. 3D printing with paraffin is not easy as the paraffin does not stay in a printable state for a longer period and is only in the state for about 2 to 3 degrees, there are new 3D printers being developed for this explicit purpose to obtain better prints and produce more efficient motors.

In essence, recent strides in hybrid rocket propulsion are characterized by advancements in fuel and oxidizer technology, additive manufacturing, motor design optimization, regenerative cooling integration, test facility development, exploration of diverse applications, and safety enhancement initiatives. These developments collectively push the boundaries of hybrid rocket technology towards higher performance, reliability, and safety standards.

The development of additive manufacturing technologies, such as 3D printing, has altered rocket fuel preparation and structural design. Yu et al. [4] conducted combustion tests on hybrid rocket fuels made via 3D printing and examined the combustion characteristics of many popular polymer materials that may be additively produced by fused deposition.

Makled reported on fuel grain geometry, operating parameters, and the design and selection criteria of hybrid rocket motor propellant (solid fuel, gas or liquid oxidizer, and energetic additives). More complex hybrid grain arrangements are described by the three fundamental elementary geometries: tube, pie-shaped, and triangular ports. Therefore, it is possible to determine the fuel grain cross-section area, burning perimeter, effective port area, filling coefficient (more than 50%), and sliver ratio (about 6%). In-depth static tests for small-scale hybrid rocket motors have been conducted using gas oxygen as an oxidant and a variety of solid fuel sources, including polymethyl methacrylate (PMMA), polyethylene (PE), PE + AL (Polyethylene - Aluminium), paraffin, and beeswax [5].

By altering the number of ports and diameter while reducing the length, a multiport design with an ideal O/F ratio was taken into consideration in order to increase the fuel's volumetric efficiency. The final port diameter was estimated, and port layout to avoid port merging was taken into consideration in order to maximize the O/F ratio. Compared to single-port fuel, the length of the fuel content decreased to 30% when there were 14 ports. With more ports and shorter fuel length at the same oxidizer mass flow rate, the testing result indicated a modest decrease in the O/F ratio while increasing the characteristic velocity efficiency [6].

Alkuam and Alobaidi [7] examined the technical developments that have occurred in the creation of these motors since 1995. Techniques for evaluating the rocket plume spectroscopically for products of combustion reactions and testing the thrust from rocket motors have been developed. Through these evaluations, researchers can gain a more thorough understanding of how physical design modifications and additions affect thrust development and regression rates. Numerous rocketry applications, such as big launch vehicles and tactical rockets, have tested or employed hybrid rocket motors. A number of additives, such as guanidinium azotetrazolate (GAT) and other aluminum alloys, have demonstrated notable increases in thrust and regression rates. Research on nanoparticle additives has produced the most recent findings [7].

The goal of the Oztan and Coverstone's [8] study was to compile and contrast research papers on additively manufactured components and hybrid rocket fuels. Because of its intrinsically low regression rate and true specific impulse, hybrid rocket propulsion has limited usage in launching applications. Various additive manufacturing techniques have been used up to this point to create fuel grains with intricate port geometries or composite fuel grains with intricately structured, printed scaffolds that integrate a second fuel material in order to overcome these limits [8].

Veale et al. [9] provide a succinct overview of all current regression rate testing methods, findings on hybrid propellants based on paraffin wax, and available structural testing data.

An overview of several methods to enhance the mechanical and ballistic performance of hybrid rocket fuel is provided in the work of Pal et al. [10].

The main issues with combustion, reaction mechanism design, low regression rate, selecting the appropriate fuel, and poor mechanical qualities were highlighted by Srivastava and Thakur [11]. The scientific community will benefit from this review by developing cutting-edge technologies that will address present issues and produce long-lasting results. However, the majority of the works have not yet made this technology commercially viable [11].

The history and basic combustion processes of hybrid rocket engines were supplied by Gerald J. Micklow [12]. It is found that the fuel grain regression rate is the main factor influencing a hybrid

rocket's performance and design. When compared to solid and liquid rockets, hybrid rocket engines have significantly reduced regression rates when used on a large scale. In order to improve the performance and efficiency of hybrid rockets, the paper examined research on regression rates and the numerous related, significant aspects that affect them. The ability to create fuel grains with helical ports through additive manufacturing techniques greatly improves heat transfer and, thus, raises the fuel grain regression rate [12].

CONCLUSION

In the realm of rocket engineering, hybrid rocket propulsion offers a strong substitute by combining the adaptability of liquid oxidizers with the simplicity of solid fuels. The combustion efficiency, safety, and environmental sustainability of hybrid rocket propellant grains have significantly increased due to recent developments in production processes and material compositions. Although there are still issues, especially with optimizing thrust and attaining steady combustion, hybrid rocket technology is ready to help the upcoming generation of space and defence missions. Unlocking the full potential of hybrid rockets in the quickly changing aerospace landscape will require ongoing study in material science, grain geometry, and propulsion testing.

REFERENCES

1. Funami Y, Takano A. Regression-rate evaluation of hybrid-rocket fuel grain with a star-fractal swirl port. *Trans Japan Soc Aero Space Sci.* 2023; 66 (3): 61–69. doi: 10.2322/tjsass.66.61.
2. Bresler J, Natan B. Experimental investigation of ABS-paraffin 3D printed hybrid rocket fuels. In: *AIAA Propulsion and Energy 2019 Forum*, Indianapolis, IN, USA, August 19–22, 2019. doi: org/10.2514/6.2019-4094
3. Yu X, Yu H, Zhang W, DeLuca LT, Shen R. Effect of penetrative combustion on regression rate of 3D printed hybrid rocket fuel. *Aerospace.* 2022; 9 (11): 696. doi: 10.3390/aerospace9110696.
4. Yu X, Yu H, Gao H, Zhang W, DeLuca LT, Shen R. 3D printed different polymer fuel grains for hybrid rocket engine. *FirePhysChem.* 2024; 4 (2): 139–145.
5. Makled AES. Hybrid rocket motor: propellant selection and fuel grain. In: *8th International Conference on Chemical & Environmental Engineering*, April 2016. pp. 261–281. doi: 10.21608/iccee.2016.35125.
6. Ahn B, Kang H, Lee E, Yun Y, Kwon S. Design of multiport grain with hydrogen peroxide hybrid rocket. *J Propulsion Power.* 2018; 34 (5): 1189–1197. doi: 10.2514/1.B36949.
7. Alkum EA, Alobaidi WM. Experimental and theoretical research review of hybrid rocket motor techniques and applications. *Adv Aerospace Sci Technol.* 2016; 1 (3): 71–82.
8. Oztan C, Coverstone V. Utilization of additive manufacturing in hybrid rocket technology: a review. *Acta Astronaut.* 2021; 180: 130–140.
9. Veale K, Adali S, Pitot J, Brooks M. A review of the performance and structural considerations of paraffin wax hybrid rocket fuels with additives. *Acta Astronaut.* 2017; 141: 196–208.
10. Pal Y, Mahottamananda SN, Palateerdham SK, Subha S, Ingenito A. Review on the regression rate-improvement techniques and mechanical performance of hybrid rocket fuels. *FirePhysChem.* 2021; 1 (4): 272–282.
11. Srivastava S, Thakur AK. Review on hybrid rocket engine: past, present and future scenario. *Int J Veh Struct Syst.* 2022; 14 (5): 680–685.
12. Micklow GJ. Additive manufacturing of fuel grains for hybrid rocket motors for increased efficiency. *J Multidiscipl Eng Sci Techno.* 2021; 8 (5): 13968–13973.