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PRELIMINARY EXPERIMENTAL EVALUATION OF THE BURNING OF PARAFFIN-BASED FUELS SUPPORTED IN POLYMERIC MATRICES APPLIED TO HYBRID ROCKET MOTORS

Mariana Conti Tarifa

Leonardo Henrique Gouvêa

Pedro Teixeira Lacava

Instituto Tecnológico de Aeronáutica, São José dos Campos, São Paulo, Brazil

mariana.tarifa@ga.ita.br

gouvea@ita.br

placava@ita.br

Abstract. *Paraffin-based fuels applied to hybrid rocket motors have been the subject of studies since the early 2000s, due to their high rate of regression in relation to those commonly used, such as Hydroxyl Terminated Polybutadiene (HTPB). However, the pure paraffin grain may present low mechanical strength and considerable unburnt fuel ejection from the rocket engine nozzle. Among the methods that have been used to suppress these undesirable characteristics are the addition of different materials amid the paraffin grain and the use of afterburners. Polymeric matrices obtained by additive manufacturing allow complex geometries in an agile, flexible and less costly way using materials that in essence also have fuel characteristics, such as acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA). In this view, the current project evaluated the influence that the support of polymeric matrices made of ABS in paraffin-based fuels can have on the improvement of grain mechanical strength, flow turbulence and burning efficiency. The experiments were carried out in a two-dimensional chamber with a visualization window in which the analysis of the spatial behavior of the regression of fuels were made. Improvements were observed in the ease of ignition and reduction of ejected paraffin.*

Keywords: *hybrid rocket motors, paraffin-based fuels, additive manufacturing*

1. INTRODUCTION

In recent discussions about access to space, hybrid propulsion technology has emerged as a promising solution for small launch vehicles due to its advantages over the solid and liquid propulsion systems (Schmierer *et al.*, 2019). In hybrid propulsion, the fuel and oxidizer are stored separately both physically and by phase, which brings intrinsic safety in manufacturing, storage and operation to the system, thus, less cost associated. Furthermore, the hybrid propellant pairs can produce specific impulse comparable to liquid bi-propellant and greater than solid propulsion systems.

The development of hybrid propulsion technology dates back to the late 1930s (Altman, 1991). However, the difficulties of achieving high regression rates with the commonly used solid fuels such as hydroxylated polybutadiene (HTPB) presented a major drawback for practical applications. Only after the study of liquefying fuels in the late 1990s, with paraffin-based formulations, its development has been considered for potential projects. Researchers at Stanford University found out that paraffin-based fuels could reach up to 3 to 4 times higher regression rates than the classic hybrid fuels (Karabeyoglu, 2004).

Nevertheless, paraffin-based fuel grains present disadvantages such as low mechanical strength and considerable unburnt fuel ejection from the rocket nozzle. Among the methods that have been used to suppress these undesirable characteristics are the addition of different materials amid the paraffin grain, such as carbon black, aluminum, metallic particles and the use of afterburners.

By printing polymeric matrices by additive manufacturing it is possible to obtain complex geometries in a flexible way using materials that in essence also have fuel characteristics, such as acrylonitrile butadiene styrene (ABS). Studies proved the viability of using ABS as a hybrid rocket fuel (Whitmore *et al.*, 2013). Other materials such as ABS, Acrylonitrile Styrene Acrylate (ASA), PLA, PLA with Aluminum, Polyethylene Terephthalate Glycol (PETG), Nylon and Polypropylene (PP) were tested and the regression rate of each propellant pair was analyzed and compared (McFarland and Antunes, 2019). Polymeric matrices made of ABS, Nylon and PLA filled with paraffin-based fuels have been also targets of recent

studies that showed the potential of additive manufacturing applied to hybrid propulsion (Pabarcus, 2019), (Bisin *et al.*, 2020) and (Lyne *et al.*, 2018).

In this view, the purpose of this work is the preliminary study of the influence that the support of polymeric matrices obtained by additive manufacturing in paraffin-based fuels can have on the improvement of flow turbulence, decrease in fuel ejection and the regression rate. Experiments were carried out in a two-dimensional combustion chamber to understand, mainly visually, the phenomena related to the burning of the hybrid propellant pair.

2. HYBRID PROPELLANT PAIRS

In most hybrid rocket motors, the most commonly used configuration is solid fuel and a liquid or gaseous oxidizer. For the current project it was chosen gaseous oxygen as oxidizer. Hybrid rocket fuels can be divided into two categories, the classic fuels and liquefying fuels. Among the classical fuels it can be mentioned HTPB, polymethyl methacrylate (PMMA) and high-density polyethylene (HDPE). Some additive manufactured materials such as ABS, ASA, Nylon and PLA also have fuel characteristics and fall into the classical fuels category. In the combustion process of classic hybrid fuels, a reactive boundary layer is formed over the fuel surface, in which a diffusion flame region is developed. It is assumed that pyrolysis occurs in the wall and the fuel enters the boundary layer in a gaseous state through convection and diffusion. Meanwhile, the oxidizer coming from the mainstream is introduced to the boundary layer through turbulent diffusion and when the mixture ratio between the fuel and oxidizer is appropriate, the combustion process starts.

In liquefying fuels, such as paraffin-based fuels, a thin liquid layer with low viscosity is created on the surface of the fuel that presents low tension. Thus, the mass transfer due to droplets adds up to the heat transfer phenomena that occurs in classical fuel configurations. Liquefying fuels can have regression rates up to 3 times higher than classical fuels (Karabeyoglu *et al.*, 2002).

In Figure 1 it is possible to observe the values for characteristic velocity obtained through a thermochemical simulation of the different hybrid fuels combined with oxygen in a Oxidizer-to-Fuel ratio (OF) range from 4 to 6. The characteristic velocity (c^*) describes the performance of different propellant pairs, thus, the higher value for c^* the more energetic the fuel and oxidizer combination is (Sutton and Biblarz, 2016). Pure paraffin-based fuel combined with a 15% ABS fuel provides a higher performance parameter when compared to other fuels analyzed and slightly lower results when compared to pure paraffin and HDPE.

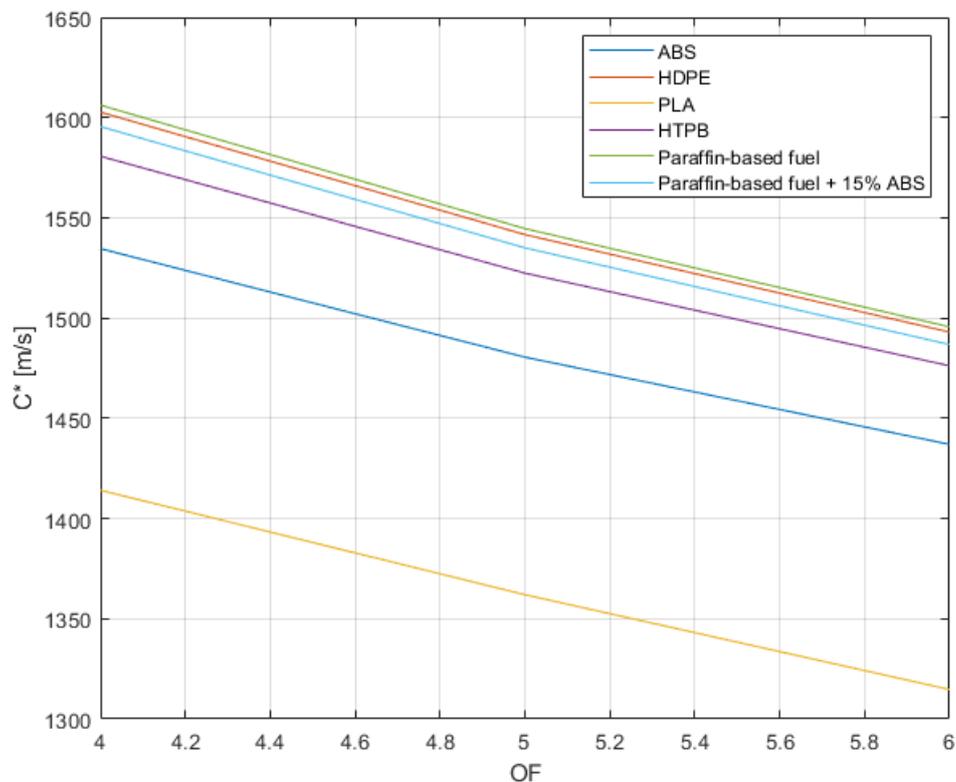


Figure 1. Theoretical characteristic velocity (c^*) for various fuels combined with oxygen.

As aforementioned, among the methods used to mitigate the undesirable characteristics of paraffin is the use of additive manufacturing to reinforce the fuel grain.

ABS has been considered a promising fuel option for hybrids mainly due to its thermodynamic and mechanical properties and higher regression rates compared to other classical fuels (Whitmore *et al.*, 2015). Therefore, it was chosen as the material for the polymeric matrix in this work.

3. EXPERIMENTAL SETUP

3.1 Combustion Chamber

The main problem concerning metallic combustion chambers in hybrid rocket motors is the access to data related to local regression rate. The conventional methods of regression rate measurement provide only local average and temporal data that are not suitable to the main investigation in this project. Thus, it was proposed the analysis of the temporal and spatial behavior of the regression of fuels in a two-dimensional chamber with a visualization window, so as to observe how the polymeric matrices geometries influence the combustion efficiency and regression rate during the burn.

The two-dimensional combustion chamber consists of an apparatus whose main objective is the observation of chemical and physical phenomena involved in combustion, in order to obtain visual and qualitative data. Inside the chamber, the fuel grain must have rectangular geometry in order to adapt to the viewing window, as observed in the experiments in (Nakagawa and Hikone, 2011), (Chandler, 2012) and (Gouvêa, 2016). The window is made of quartz, similar to Pelletier, Nakagawa and Gouvêa. The flow of gaseous oxygen comes from a feeding line and is injected into the two-dimensional chamber, as indicated in Figure 2.



Figure 2. Two-dimension combustion chamber with a quartz visualization window.

3.2 Feedline System

The feedline system constitutes a line responsible for circulating gaseous oxygen, which is taken to the chamber to perform the test in environment pressure. It was necessary to have a pressure regulator in the oxygen cylinder, an electropneumatic valve controlled by the control system to open and close the oxygen flow, a flow meter and a check valve that prevents the return of the flame to the line. A needle valve at the beginning of the line has also been added to allow for flow control during the test, if necessary. An schematic of the feed line system is presented in Figure 3.

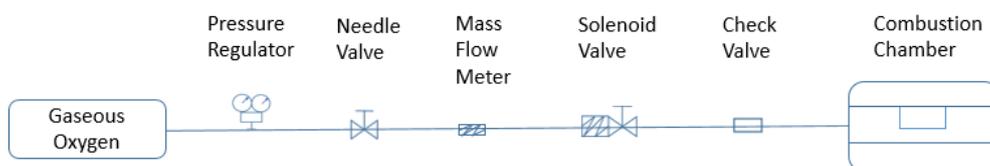


Figure 3. Feedline system.

Ignition takes place when there is a reaction in which a rapid heat transfer or flame occurs in a flammable mixture. For

the ignition of the present project, a system consisting of a 12V battery, a Ni-Cr wire and a small piece of double-base, a flammable material, was devised. As soon as the test start is activated in the program developed in LabView, the current that comes from the battery heats the Ni-Cr wire, which causes the double-base to ignite. From this procedure, the fuel grain is finally ignited.

3.3 Fuel Grain Configuration

The fuel grains consisted in blocks with the main dimensions shown in Figure 4, in which LxHxC is 20x20x100mm, respectively. For the fuel grains consisted of paraffin and ABS, the paraffin was casted inside the polymeric matrix.

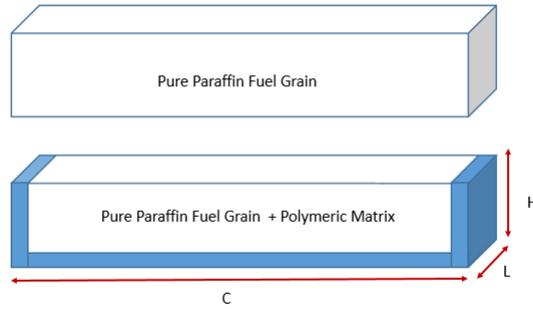


Figure 4. Schematic model of the fuel grains.

The thickness of the ABS matrix was established as 2mm. For purposes of preliminary study, only two thins were considered in the analysis.

3.4 Regression Rate Measurement

The camera was positioned above the combustion chamber so that the regression rate could be obtained visually. The camera had a capacity of 60 frames per second and the images were analyzed in intervals of 6 seconds, since the burning rates of the fuel grains are low.

An imaging software was developed in order to obtain the instant values for regression rate. Therefore, a per-pixel analysis was made for each frame so that a instantaneous measurements could be done. With these values, it was possible to calculate the mass flux of oxidant and as well as the regression rate, considering spatial average for both. Figure 5 illustrates the grain configuration and the main parameters associated.

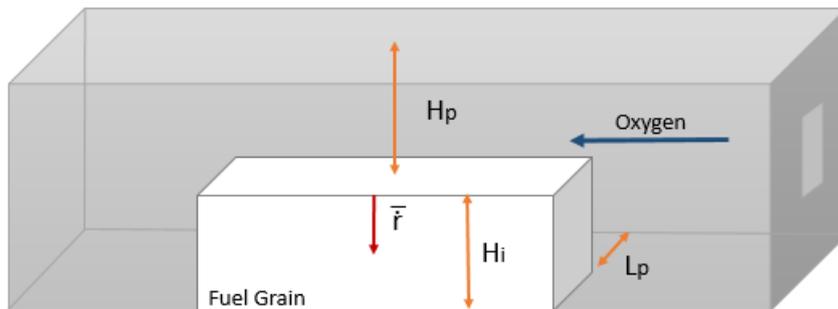


Figure 5. Grain configuration inside the chamber and main parameters associated.

Thus, the regression rate was obtained through Equation 1, in which H_i is the initial height of the grain and H_f is final height of the grain after being consumed, measured in millimeters. The parameters t_i and t_f are the initial and final time in seconds, respectively.

$$\bar{r} = \frac{\overline{H_i} - \overline{H_f}}{(t_f - t_i)} \quad (1)$$

The average oxidizer mass flux is given by Equation 2, in which \dot{m}_{ox} is the oxidant mass flow rate in kg/s and \overline{A}_p is the mean combustion port area, which is the length L_p multiplied by the height H_p indicated in Figure 5.

$$\overline{G_{ox}} = \frac{\dot{m}_{ox}}{\overline{A}_p} \quad (2)$$

4. RESULTS

The burning of pure paraffin and paraffin with ABS matrix can be seen in Figure 6 in three different moments of the test: the ignition and two different time intervals, from top to the bottom. After the fuel grain is ignited, a low viscosity liquid layer is formed over its surface and a flame develops entirely through this surface. An ease of ignition was observed in the fuel grains that contained the ABS matrix when compared to the pure paraffin grains.

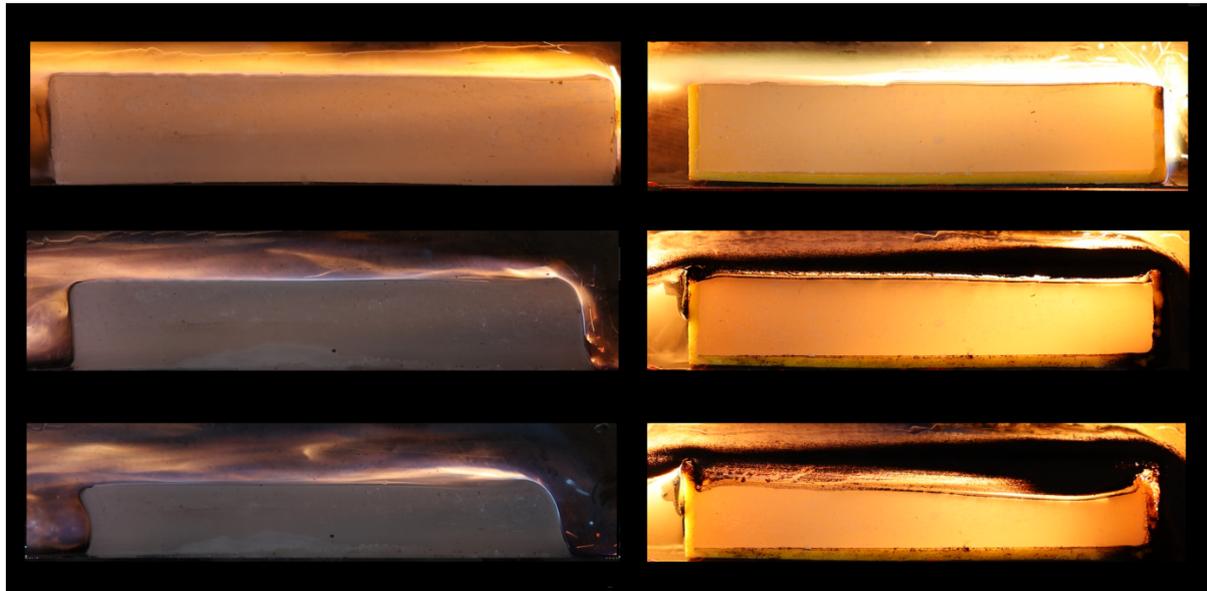


Figure 6. Pure paraffin and paraffin with ABS matrix burning test.

In this work, the decrease in the ejection of paraffin was considered as a parameter of burning efficiency. The initial mass of the grain and the ejected paraffin mass after burning test were measured and compared. The paraffin grains inserted in the ABS polymeric matrix presented values over 50% higher than pure paraffin grains in terms of decrease in the ejection of paraffin. In 1, the values for decrease in ejected paraffin were shown in terms of percentage, indicating how much better the ABS matrix and paraffin burning was compared to the pure paraffin burning.

Table 1. Comparison between ABS matrix/paraffin and pure paraffin fuel grains in terms of decrease in ejected paraffin.

Fuel Grain Configuration	ABS Matrix and Paraffin - Sample 1	ABS Matrix and Paraffin - Sample 2
Pure Paraffin - Sample 1	64.3%	69.8%
Pure Paraffin - Sample 2	52.2%	57.8%

Since the paraffin grain, a liquefying fuel, has higher regression rate than the ABS matrix, which has a combustion process like classical fuels, a recirculation zone is formed in this gap region, which helps the paraffin to vaporize more, therefore, burn more. In Figure 7, the blue circle indicated the recirculation zone being formed in the first seconds of the test. Moreover, in this image it is possible to observe the liquid layer in the surface of the paraffin.

The results that compare pure paraffin and ABS matrix with paraffin are shown in Figure 8. Two samples of each configuration were tested. It was observed that the samples that were added to an ABS polymeric matrix presented slightly lower results for regression rates. This fact can be explained by the different combustion process presented by both fuels. As discussed previously, while paraffin falls into the liquefying fuel category, ABS falls into the classical fuels category that present very low values for this parameter. However, the difference can be considered small and it still represents a major advantage when compared to pure conventional fuel grains such as HTPB, that present even lower regression rates for the similar range of GOX studied in this work (Cardoso *et al.*, 2019).

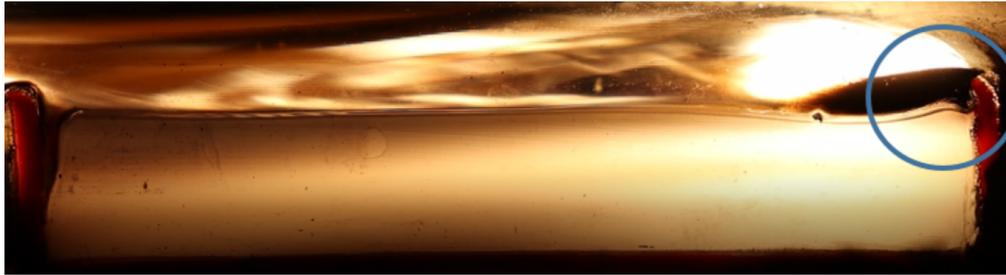


Figure 7. Recirculation zone indicated in the burning of paraffin and ABS matrix.

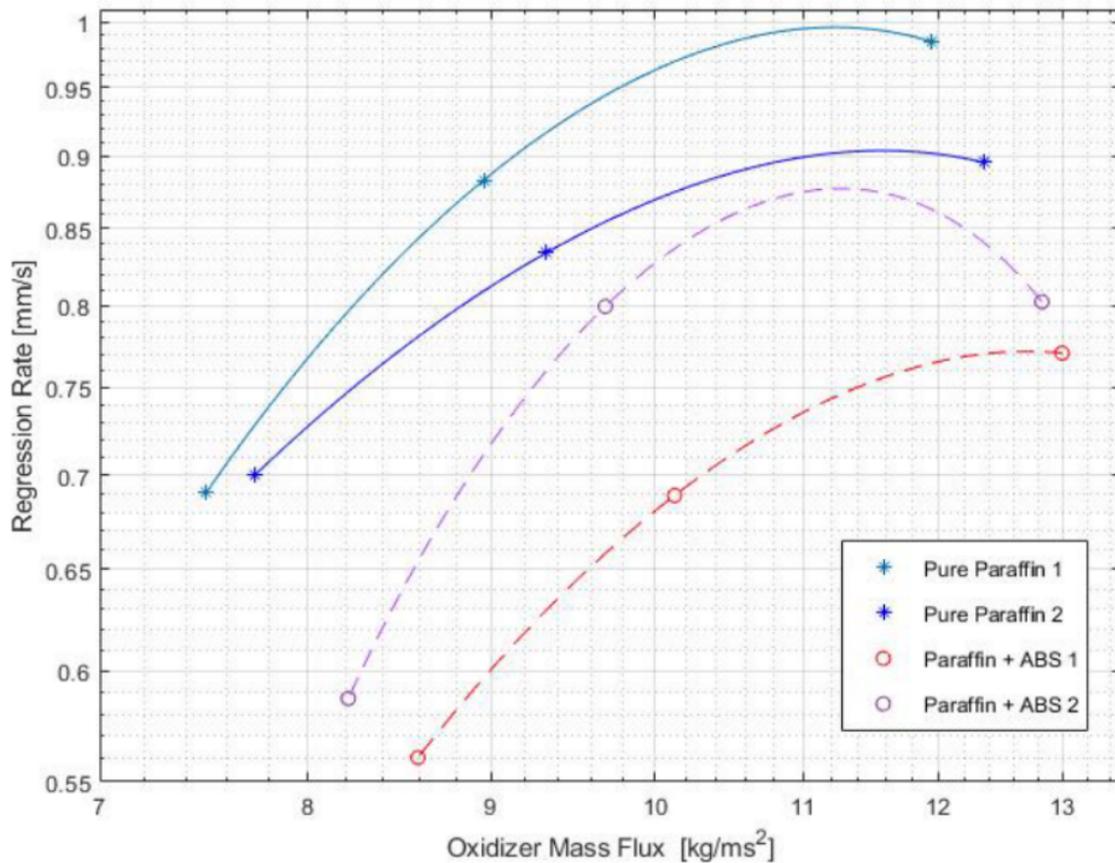


Figure 8. Regression Rates comparison between Pure Paraffin and Paraffin with ABS matrix.

5. CONCLUSION

This work consisted of a preliminary study that aimed at the comparison of the burning of paraffin-based fuels supported in polymeric matrices using a two-dimensional combustion chamber with a quartz visualization window.

The methodology adopted generated visual results, allowing a deeper analysis of the behavior of the fuel grains combustion processes and key aspects to understand the main differences between both grain configurations studied, such as the ease of ignition and recirculation zones formed in the presence of ABS thins. Furthermore, regarding the regression rates, it allowed obtaining multiple values in just one test performance, against the traditional regression rates measurement methods.

The presence of ABS matrix improved the values regarding the decrease of ejected paraffin, with values above 50%, due to the recirculation zone formed between both fuels, that helped better vaporize paraffin.

Moreover, the regression rate values for the paraffin and ABS matrix were slightly lower than pure paraffin fuel grains. However, it still represents an advantageous alternative when compared to classical fuels.

Future work will contemplate other geometry parameters in the polymeric matrix, such as the addition of more thins and different angles relative to the oxidizer flow. Furthermore, analysis with a high speed camera will help understand the difference in ignition time, visualize unburnt paraffin ejection and recirculation zones.

6. ACKNOWLEDGEMENTS

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