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REVIEW OF REGRESSION RATE ENHANCEMENT TECHNIQUES FOR HYBRID ROCKET ENGINES

C. Glaser^{1*}, J. Hijlkema¹, J. Anthoine¹

¹ ONERA/DMPE, Université de Toulouse, F-31410 Mauzac, France

*christopher.glaser@onera.fr

ABSTRACT

Hybrid Rocket Engines (HREs) generate thrust by combining a liquid and a solid propellant. Given the hybrid nature, HREs possess several advantages over Liquid Rocket Engines (LREs) and Solid Rocket Motors (SRMs). Hybrid engines are cheaper and less complex than LREs while being safer and more sustainable than SRMs. HREs are throttleable as well as re-ignitable and their theoretical achievable specific impulses (I_{sp}) lie between SRMs and LREs. However, hybrid engines suffer from several disadvantages that refrained them from reaching their full potential yet. Among other drawbacks, HREs have a low maturity, high fuel residuals and a low solid fuel regression rate. In fact, the low regression rate is considered the limiting characteristic for HRE applications. Around the globe, great research effort is put into enhancing the regression rate. Summarizing, the authors group the techniques together as a) adjusting the solid fuel properties, b) advanced injection methods and designs and c) improving the combustion chamber design. Each of these techniques comes with a different set of advantages and drawbacks, which need to be considered when designing a HRE.

Keywords: Hybrid Engines, Regression Rate, ASCenSIon

1 INTRODUCTION

Although the first recorded launch of a hybrid rocket was already on August 1933 in the USSR [1], as of today, HREs are not mature enough to be reliably utilized in rocket propulsion. Given that HREs have – in theory – a better performance than solid engines and are less complex and more sustainable than liquid propulsion, this could signify a huge unused potential for the future space segment. For example, Casalino *et al.* [2, 3, 4, 5] postulated that substituting the solid third (Zefiro 9) and liquid fourth (AVUM) stage of Vega with a single HRE would lead to a payload increase between 400 and 1,000 kg (in the case of electric pump feeding). The advantages and disadvantages of HREs have been already thoroughly discussed in previous literature (e.g. [6]), at this point the focus lies on the low regression rate of HREs and the enhancement techniques thereof. The low solid fuel regression rate (usually in the order of 1 mm/s) is considered the major drawback for HREs. In order to understand the reason for low regression rates of HREs, it is necessary to study the hybrid combustion mechanisms. Contrary to solid (where fuel and oxidizer are pre-mixed in the grain) and liquid (where the propellants are mixed in the combustion chamber during injection) propulsion, for hybrids, the propellants are stored separately and in different states. Because of this, the combustion process inside HREs is fundamentally different. As displayed in Figure 1, the combustion is defined by a turbulent boundary layer with a thin diffusion flame zone that forms itself typically at about 10-20% of the boundary layer height [7]. Convective, diffusive and radiative heat transfers provide enough energy at the fuel surface to support the pyrolysis process which itself again provides enough fuel to sustain the combustion. The rate in which the solid fuel regresses is referred to as regression rate.

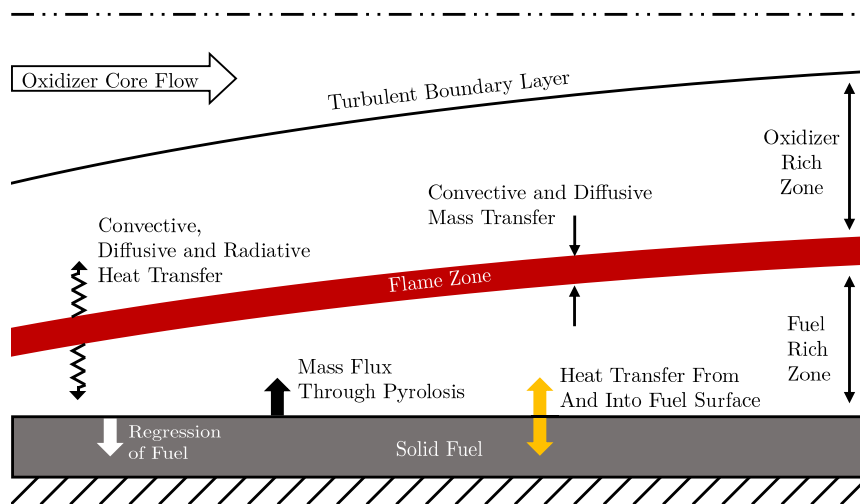


Figure 1: Combustion inside HRE (based on [43])

Knowing the physics of the HRE combustion, it can be observed that mainly two effects dominate: The heat transfer to the fuel surface and the fuel pyrolysis. This is where most of the regression rate enhancing ideas originate.

2 CONTROLLING THE SOLID FUEL PROPERTIES

The first group of regression rate enhancing methods concerns itself with the solid fuel, meaning changing the type of the fuel completely (e.g. liquefiable fuels, energetic binders) or mixing additives into the fuel matrix to decrease the heat of sublimation or creating a more energetic fuel.

2.1 Liquefiable fuels

In 2002, Karabeyoglu *et al.* [8, 9] discovered (based on observations of cryogenic fuels) that some materials form a liquid melt layer on the fuel surface rather than sublimating from solid phase to gaseous phase. The layer gets unstable and the fuel droplets are entrained in the flow and into the diffusion flame. Typical candidates are solid, frozen H_2 or non-polymerized substances such as paraffin wax (which is the most prominent one). Using paraffin, Karabeyoglu *et al.* achieved regression rates 200% – 300% higher than with conventional fuels. The major two hypotheses to explain the significantly increased regression rates are: 1) The energy (heat) to vaporize paraffin is reduced and the enthalpy difference between flame and fuel is lower 2) In classic hybrid theory, the blocking effect from the fuel surface (mass flow from fuel surface blocks incoming heat) plays a major role. In liquefiable theory, however, the liquid droplets that are entrained can be ignored for the blocking effect.

Nonetheless, paraffin has poor structural properties and the overall combustion efficiency is lower due to unburnt, entrained fuel particles. Especially the mechanical properties are a concern when it comes to scaling up paraffin-based fuels [10]. Several additives (e.g. styrene) have shown to increase the mechanical properties with the downside of affecting the liquid melt layer. An overview of several paraffin additives is found in [11]. Nonetheless, several hybrid launcher start-ups (such as HyImpulse [12], Equatorial Space System [13] and Space Forest [14]) are developing paraffin-based hybrid engines due to their naturally increased regression rates.

2.2 Fuel additives

Adding nano- or micron-sized particles to the solid fuel grain can significantly increase the performance of the hybrid engine. While the additives do not directly increase the regression rate, in general, additives in the fuel increase the combustion temperature and specific impulses and introduce a more dominant radiative heat transfer. Because of the aforementioned effects, the regression rate increases [15]. The list of potential candidates for additives (mostly metals) is very extensive and out of the scope for this short review. For a more detailed overview, it is referred to Risha *et al.* [16] or more recently Karabeyoglu [15]. The most common candidates for additives are lithium-, aluminium-,

magnesium- or boron-based. For example, Qin *et al.* [17] were able to increase the regression rate up to 83% by adding amorphous aluminium to HTPB (Hydroxyl-Terminated Polybutadiene). Regarding aluminium additives, an extensive research was carried out by Paravan [18]. The US Air Force Sandpiper Target Missile and Lockheed Martin's HYSER program are prominent examples of flight-tested engines with additives [16]. However, price considerations (especially for the nano-regime additives) and unclear impacts of metal additives on the environment make the use of additives both highly interesting and delicate at the same time [15].

Another possibility to increase the regression rate is to insert solid oxidizer particles into the solid fuel. Examples are ammonium perchlorate or ferric oxide (also used as catalyst in solid rocket motors). Results of these mixed hybrid concepts have shown increments from the HTPB base reference from 176% in the case of ammonium perchlorate and up to 447% adding also ferric oxide as catalyser [19]. However, in doing so, the solid fuel is no longer inert and the hybrid engine loses this important advantage. A similar approach (while technically not being a fuel additive) is changing the binder type from a non-energetic type (like HTPB) to an energetic binder like Glycidyl Azide Polymer (GAP) [20]. Wada *et al.* [21] compared the regression rates of pure, inert PEG (Polyethyleneglycol) with mixtures of PEG and the energetic GAP and observed significantly increased regression rates, approximately 200% higher. Nonetheless, using energetic binders comes with the same downsides as solid oxidizer additives, namely the loss of fuel inertness.

3 ADVANCED INJECTION METHODS AND DESIGNS

In the preceding section, the chemical properties of the solid fuel grain were investigated. However, how the oxidizer is injected has also a significant effect. The next two sections discuss some of the existing designs and ideas.

3.1 Head-end injection methods

In the classical head-end injection, the oxidizer is injected at the entrance of the fuel ports. This is the case for most classic hybrid rocket designs. The specific injection method, however, can have a significant influence on the regression rate. The most straightforward injection is an axial injector. Depending on how far the injection jet reaches into the fuel port, a recirculation zone is established which increases the heat transfer to the surface and the oxidizer transport. Testing different axial injection methods, Carmicino and Sorge [22] observed regression rates increased by up to 150%. Bouziane *et al.* [23] also compared different injectors. The tested designs were showerhead (axial), hollow-cone (injects the oxidizer in a bi-directional fashion resulting in a cone), pressure-swirl (the oxidizer is first introduced into the swirling chamber and then ejected through the nozzle as an annular sheet) and vortex (feeds the oxidizer in a rotating manner) injectors. For the case of hollow-cone and vortex injection, they observed above 20% regression rate increase compared to the showerhead axial case. Bellomo *et al.* [24] observed a similar trend for the vortex injection, where they achieved a regression rate 51% higher with less instabilities. These performance gains are explained with the elevated convective heat transfer due to the vorticity. The pressure swirl case of Bouziane *et al.*, however, had a 20% lower regression rate as their showerhead design. Interestingly, Bertoldi *et al.* [25] conducted experiments using a pressure swirl injector and measured a 20% increase in regression rate as compared to axial injection. Given the length difference of the combustion chamber, Bouziane *et al.* concluded that pressure swirl injectors are most efficient when the injector is close to the fuel grain, so that the oxidizer flow still has a high velocity.

3.2 Aft-end injection methods

Over the years, several aft-end injection HRE designs have been proposed, two out of which are introduced in Figure 2. With the bi-directional vortex engine from Knuth *et al.* [26] (Figure 2 a)), the oxidizer is injected through a vortex injector at the end of the combustion chamber. This way, the outer vortex propagates upwards, while the inner vortex shifts downwards. Regression rates 650% higher than in comparable HREs have been reported. The other concept, illustrated in Figure 2 b), inherits only one-directional vortexes, similar to what is found in Majdalani [27], Haag *et al.* [28], Rice *et al.* [29], Lestrade *et al.* [30], DeLuca *et al.* [31] and Glowacki *et al.* [32]. Additional to the

increased heat transfer through the induced vortex injection, the burning surface of the HREs stays constant over the duration of the burn, leading to a more consistent O/F ratio.

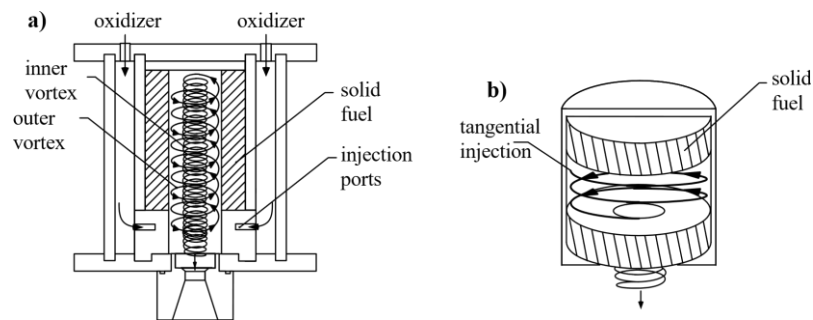


Figure 2: a) bi-directional vortex engine by [26] b) dual end burning engine (images from [27])

4 IMPROVING COMBUSTION CHAMBER DESIGNS

The combustion chamber, usually defined by the fuel port(s) of the engine, gives several possibilities to improve regression rates as explained below.

4.1 Multi-port designs

While pointing out that a multiport design is rather mitigating the effects of a low regression rate than actually enhancing it (as Pastrone [20] put it), the increase of the burning surface due to multiple ports can counter the low regression rate problem. A prominent example is the 15-port fuel grain design of the record-breaking 1,100 kN thrust HRE booster of AMROC [33].

4.2 Turbulence and heat-transfer enhancing devices

A simple, yet effective, possibility to increase the regression is adding screens, diaphragms [34], obstacles [35], turbulators [36] or steps [37] into the fuel port. Consequently, the turbulence and, thus, the heat transfer and regression rate is increased. On the other hand, this increases the risk of failure and introduces complexity depending on the detailed method. For example, a single step halfway of the fuel port increased the regression rate by 50% [38]. A single diaphragm was observed to increase the regression rate by 47% [39]. The mechanism that drives the regression rate in these cases is the establishment of a recirculation zone behind the obstacles that drastically increase mixing and heat transfer from the flame to the fuel.

4.3 Advanced fuel port profiles

Finally, the rise of additive manufacturing does also affect the HRE domain. With additive manufacturing, fuel port designs are possible that are not feasible with traditional manufacturing methods [40]. For example, Hijlkema [41] 3D-printed a fuel port profile that was optimized by a generic algorithm to minimize O/F shift (although other optimization criteria are possible too). He observed improved performance compared to the base-line tests. Whitmore *et al.* [42] 3D-printed helical port structures that forced the oxidizer to follow a helical path. The combined effect of increased skin friction coefficients and the centrifugal forces suppressing the wall blowing effect led to regression rate increases of up to 300%.

5 CONCLUDING REMARKS

In this short overview, several techniques to augment the regression rates are presented and the mechanisms driving the increase explained. This short article is not intended to be an exhaustive overview of all different designs that are being researched, but rather grouping the techniques according to their physical mode of action. In the authors views, techniques that only require low adjustments to the overall design (and can be theoretically added to existing engines) such as the group of turbulence and heat-transfer enhancing devices are of great potential. A more detailed and extensive review of different techniques will be given in a follow-up article.

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