Evaluation of Regression Rate Enhancing Concepts and Techniques for Hybrid Rocket Engines

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Abstract
The low regression rate of Hybrid Rocket Engines (HREs) is one prominent characteristic that is addressed in most abstracts concerning hybrid propulsion. Over the years, researchers developed and investigated numerous ways to tackle the low regression rate problem of HREs. This article is a collection and assessment of these diverse methods and designs. It allows for a quick overview of the different mechanisms that are being employed and can serve both as information and inspiration. The enhancement ideas are grouped together as (a) adjustments to the solid fuel chemical properties, (b) advanced injection methods and concepts and (c) improving the combustion chamber design. These different techniques are discussed and their individual impact on the regression rate is assessed both qualitatively and quantitatively. All methods that are presented come with a different set of advantages and disadvantages, making the regression rate enhancement a trade-off problem. In our view, the most promising designs and methods are those that only call for minor adjustments to the HRE design, as they can be also added to already existing engines. Above all, it is to be said that regression rate enhancing techniques that change the unique features of HREs (namely safety, simplicity and low cost) are to be employed with caution. Only if the achievable regression rate increase is justifying the implications for the HRE in the envisioned use-case, these concepts represent promising alternatives to the status quo.

Keywords Hybrid propulsion · Regression rate enhancement · Advanced hybrid engine concepts · Review

1 Introduction

Although the first recorded launch of a hybrid rocket took place already in 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 specific impulse 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. [2–5] 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 1000 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]), that is why they are only briefly summarized in Table 1.

For this work, the focus lies on the low regression rate of HREs and the enhancement techniques thereof. It is to be noted that most of the techniques to enhance the regression rate also have an influence on other aspects of the HRE behavior. The two most noteworthy are the low volumetric loading and the low combustion efficiency. The volumetric loading is dependent on the regression rate, because a higher regression rate allows for single port solutions, whereas for low regression rates, sometimes multi-port solutions (hence poor volumetric loading) are considered. As for the combustion efficiency, many regression rate increasing methods rely on increasing the turbulence inside the combustion chamber. This turbulence leads to better mixing of the propellants and, thus, an increased combustion efficiency.

The structure of this article is as follows: after the necessary physical foundation of HREs is laid, we describe the regression rate enhancement techniques grouped together
according to the physical mechanisms they exploit. Next, the increase in regression rate is quantified and the proposed designs and techniques assessed based on their complexity and regression rate improvement. This article is a continuation of [10] and an overview or starting point for the topic of regression rate enhancement. Moreover, it can serve as a source of inspiration for novel techniques and ideas. On a final note, it is to be pointed out that the presented enhancement ideas are not mutually exclusive, a combination of two (and even more) methods are theoretically possible as will be addressed in Sect. 8. To complement, all designs that are discussed in the article are collected in Table 4 of the Appendix for convenient access.

### 2 Physical Description of Hybrid Rocket Engines

The low solid fuel regression rate (usually in the order of 1 mm/s) is considered the major drawback for HREs. The implications of the low regression rate on the HRE design are discussed in Sect. 3; in this section, the causes for low regression rates are elaborated. To understand the reason for low regression rates of HREs, it is necessary to study the hybrid engine 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 Fig. 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 [11, 12]. 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 [13].

Moreover, the combustion in classical HREs can be assumed self-regulating to a certain degree. An increased oxidizer mass-flow increases the heat transfer onto the fuel surface, accelerating the gasification of the fuel. Increased fuel mass-flux from the surface, on the other hand, creates the so-called blocking (blowing) effect, since it blocks incoming heat. Therefore, after a while, a somewhat stable state of combustion is achieved [12, 13].

Knowing the physics behind 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.

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**Table 1** Advantages and disadvantages of HREs [1, 7–9]

| Advantages           | Disadvantages                          |
|----------------------|----------------------------------------|
| Simplicity           | Low regression rate                    |
| Fuel inertness       | Low volumetric loading                 |
| Sustainability\(^a\) | Low combustion efficiency              |
| Insensitive to fuel cracks | Slower transient                  |
| Throttleable         | O/F shift during operation             |
| Re-ignition possible | Regression rate estimation\(^b\)       |
| Propellant versatility | Residual fuel mass                     |

\(^a\)Depending on the propellant choice

\(^b\)This disadvantage is also shared with solid rocket motors

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**Fig. 1** Schematic view of HRE combustion [10]
3 Importance of Regression Rate on the Engine Design

Before reviewing the different methods that have been developed to increase the regression rate, it is useful to answer the question why the regression rate plays such an important role in the design of a hybrid engine. For this, we consider a parametric study published by Casillas et al. [14] at Pratt and Whitney in 1997. The work was carried out within the Hybrid Propulsion Demonstration Program (HPDP), a project succeeding the research efforts of the famous Aquila hybrid launcher concept of AMROC [15, 16] and the Hybrid Technology Option Project (HyTOP) [17]. Casillas et al. [14] investigated the influence of the regression rate on the fuel grain design and length.

The baseline requirements were derived from the first stage solid motor (Castor 120 [18]) of the Taurus [19] launch vehicle. The important key data were a 90-s burn time with a desired total impulse of 30 Mlbf-s (133.446 MNs), leading to a thrust of approximately 1482 kN. Fixing the motor diameter to almost 2.4 m (93 inches), Casillas et al. calculated in a parametric study how different values of regression rates influence the overall length and design of a 1500 kN thrust motor. The results have been re-imagined in 3D for this article for illustrative purposes and are presented in Figs. 2 and 3. The baseline regression rate was in the order of magnitude of 1 mm/s; a typical value for pure Hydroxyl-Terminated Polybutadiene (HTPB). From left to right, the regression rate used for the calculation was increased from the baseline over to a threefold regression, then a fourfold regression and finally to a 12-fold regression.

Looking at Fig. 2, the first prominent observation is the significant height difference of the grains. In order to achieve the 1500 kN thrust, the design with the base regression (approximately 1 mm/s) has to be 9.35 m tall, while already a threefold regression increase diminishes the size by 46% to 5.03 m. From a design point of view, a shorter length translates to less fuel casing cost as well as lower fuel grain cost [14]. Moreover, a shorter fuel grain
leads to a lower length-to-diameter \((L/D)\) ratio, which is especially important for upper stage applications \((L/D = 0.8–6)\) and less for booster or first stage applications \((L/D = 4–12)\) \([20]\). Interestingly, a further increase in regression rate does not necessarily decrease the length significantly. This is also due to a mechanism that can be already guessed from Fig. 2a), but becomes obvious in Fig. 3. From the base-case (left) to the highest regression rate case (right), the number of necessary ports decreased from 14 to 1, respectively.

The reason why engines with low regressing fuels often have to rely on multi-port solutions is rather simple. The higher the number of ports, the higher the burning fuel surface, hence, the fuel mass-flow and thrust \([14]\). Sometimes, those solutions are considered as a regression rate enhancing design, although a multi-port solution mitigates the low regression rate problem rather than solving it—as Pastrone \([21]\) puts it. Unfortunately, multi-port solutions lead to poor volumetric loading (usable fuel area divided by total engine cross section), high fuel residuals and increased fuel processing cost \([14]\). This is why for fast regressing fuel engines, the gain of the regression rate is used not only to shorten the grain but also to decrease the number of fuel ports. Further elaborations on multi-port solutions can be found in Sect. 6.1.

Table 2 summarizes the main characteristics of the four engine studies, where the decrease in grain length and increase of volumetric loading becomes apparent. Summarizing this section and Table 2, it is obvious why a high regression rate is a crucial parameter for the HRE; it allows for shorter fuel grains with lower number of ports, which ultimately translates to lower cost, less complexity and a lower \(L/D\) ratio. It is to be noted that although the study presented dates back to 1997, it serves as an ideal example for the influence of the regression rate on the HRE design. While the absolute values of the costs of the case and grain need to be regarded keeping in mind the available data (and inflation) from 1997, the relative cost savings still are comparable today.

|                      | Base       | Threefold | Fourfold  | 12-fold  |
|----------------------|------------|-----------|-----------|----------|
| Grain length         | 9.35 m     | 5.03 m    | 4.36 m    | 3.68 m   |
| Length reduction to baseline | –         | 46%       | 53%       | 60%      |
| \(L/D\)              | 3.95       | 2.13      | 1.85      | 1.56     |
| Number of ports      | 14         | 8         | 4         | 1        |
| Volumetric loading   | 34%        | 63%       | 73%       | 92%      |
| Sliver value\(^a\)   | 12.9%      | 12.5%     | 22.3%     | 4.5%     |
| Case and grain cost (from 1997) | 821k US-$  | 651k US-$ | 672k US-$ | 580k US-$ |
| Cost savings to baseline | –        | 20.7%     | 23.6%     | 29.3%    |

\(^a\) Fuel area at burnout divided by cross section of engine \([14]\)

4 Altering the Solid Fuel Chemical 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. It can, therefore, also be called the chemical method to increase regression rate.

Before the different chemical methods are discussed in detail, it is to be noted that utilizing propellant combinations with high oxidizer-to-fuel (O/F) ratios can also counter low regression rates, because the fuel addition due to the fuel regression rate plays only a smaller role in these systems \([21]\). Nonetheless, high O/F ratios either mean an operating condition of the engine far from the optimum, or they limit the propellant choice (nitrous oxide typically having a higher optimal O/F but having a lower specific impulse as compared to hydrogen peroxide for example). Additionally, larger oxidizer tank volumes are necessary. Dependent on the oxidizer density in relation to the fuel density, this can have a minor or major impact on the engine design. However, since high O/F operating systems are technically not a regression rate enhancing method, this mitigation approach is only stated here as a side-note.

4.1 Liquefiable Fuels

In 2002, Karabeyoglu et al. \([22, 23]\) 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 instable and the fuel droplets are entrained in the flow and into the diffusion flame. The most prominent materials are non-polymerized substances such as paraffin wax. On the cryogenic spectrum, solid, frozen \(H_2\) or methane are possible candidates. Using paraffin, Karabeyoglu et al. achieved regression rates 200–300% higher than with conventional
fuels. They formulated three hypotheses to explain the significantly increased regression rates [22, 23]:

1. The energy (heat) to vaporize the solid fuel is reduced. Additionally, the enthalpy difference between the flame and the fuel (now liquid) 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.
3. The liquid melt layer is not flat and smooth but unstable and rippled. This increases the surface roughness, which as a consequence increases regression rates. However, it is assumed that this factor is relatively small compared to the other two mechanisms.

Nonetheless, paraffin has poor structural properties (e.g., high brittleness) and the overall combustion efficiency is assumed lower due to the unburnt, entrained fuel particles. Especially, the mechanical properties are a concern when it comes to scaling up paraffin-based fuels as observed by [24]. Several additives (e.g., polymers) have shown to increase the mechanical properties with the downside of affecting the liquid melt layer. An overview of several paraffin additives can be found in [25]. Low melting point polymers (e.g., polystyrene-based) are also investigated. They are able to achieve regression rates comparable to paraffin while having elevated mechanical properties, but possibly increase pressure dependency of the regression rate [26].

A noteworthy approach to the poor mechanical properties of paraffin is to apply reinforcing structures inside the paraffin grain. This method is called either armored grain [27, 28] or nested structure [29], depending on the author or institution. These structures have also shown to increase the regression rate. For Bisin et al. [27, 28] it is a positive side effect, while Wang et al. [29] aimed for reinforcing structures that induce a helical oxidizer flow. This method is feasible for pure paraffin waxes but also for blended paraffin fuels. Using a nylon-based grain insert, the armored grain was able to increase the yield strain by 296% and the yield stress by 35% [28]. The remarkable side effect that was noted, was that the regression rate also increased by 35–55% as compared to the baseline [27]. The authors explained the augmented regression rate with an elevated fuel surface roughness introduced by the reinforcement structure since the paraffin wax burns faster than the 3D-printed insert. This leads to a rough fuel surface, increasing the skin friction and turbulence and, hence, the regression rate [27]. For Wang et al. [29], the goal was to increase the regression rate, not 'only' as a side effect. The nested helical ABS structure aims at inducing a swirling flow that increases the regression rate, because the wax burns faster than the ABS helix. Figure 4 displays the helical structure that is added inside the paraffin grain. Experiments yielded regression rate increments of 20% at low mass-fluxes, which the authors suspect to increase with increasing oxidizer mass-flux.

Despite the aforementioned challenges, several hybrid launcher start-ups such as HyImpulse [30], Equatorial Space System [31] and Space Forest [32] are developing paraffin-based hybrid engines due to their naturally increased regression rates.

4.2 Doping the Fuel with Additives

In Sect. 4.1, structural enhancement additives for paraffin were shortly introduced. In this section, however, performance enhancing additives such as metals, carbon, hydrides and oxidizing agents are discussed and also their impact on the environment evaluated.

4.2.1 Metal 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, specific impulse, density and introduce a more dominant radiative heat transfer. Because of the aforementioned effects, the regression rate increases [33, 34]. The US Air Force Sandpiper Target Missile and Lockheed Martin’s HYSER program are prominent examples of flight-tested engines with additives [34]. The list of potential metal candidates as additives is very extensive and out of the scope for this review. For a more detailed overview, the reader is referred to Risha et al. [34] or more recently Karabeyoglu [33]. The most common candidates for additives are lithium-, aluminum-, magnesium- or boron...
based. For example, Qin et al. [35] were able to increase the regression rate up to 83% by adding amorphous aluminum to HTPB. Regarding aluminum additives, an extensive research was carried out by Paravan [36]. While nano-sized particles are considerably more expensive than micron-sized (down to 2 μm) particles, they are preferable from a performance point of view [33, 34]. For example, nano-sized particles have a shorter ignition delay, a shorter burn time and achieve a higher specific particle density. According to the $d^2$ law, the burn time decreases by 100 if the particle diameter is ten times smaller [34]. Hence, it is necessary to trade-off possible performance gains with the cost.

A common downside of metal additives are agglomeration and aggregation phenomena, where metal oxides form a melt/coal layer on the fuel surface, that not only limits regression rate and thermal transfer but also breaks free (referred to as chuffing [37]) and impinges for example on the nozzle [21, 36]. These effects signify that the amount of metal additives needs to be thoroughly evaluated and does not necessarily increase with higher additive mass fractions.

Transition metals (iron, nickel and copper) and acetylacetonate complexes in the HTPB fuel matrix have been proven to decrease the thermal stability of the fuel. The complexes catalyze the pyrolysis of HTPB [38]. For example, Yu et al. [39] exhibited a 25.5% increase in regression rate compared to the HTPB and gaseous oxygen (GOX) baseline by adding 5 wt-% Nickel acetylacetonate (Ni(acac)$_2$) to the fuel. At 40 wt-%, however, the regression rate decreased; hinting again to the existence of an optimal amount of percentages for each additive.

A very effective heat transfer enhancing device for solid rocket motors are embedded wires in the fuel grain, with significant (around 400% increase) improvements to the regression rate [40, 41]. It has, thus, been tested also in hybrid rocket engines [41, 42]. For this, metallic wires are embedded into the fuel grain, perpendicular to the mass-flow. The wires are supposed to increase the heat transfer into the fuel grain due to their enhanced conduction. Unfortunately, the results with metallic wires in HREs have not been promising. Shin et al. [41] experimentally tested silver and copper wires with diameters ranging from 1.5 to 2 mm. The regression rate increase was only 2.14–3.7% as compared to the baseline, favoring larger diameters. The authors concluded that the reason for wires not being effective in HREs is that the HRE fuel is inert. Therefore, additional heat transfer to the fuel grain is only increasing the regression rate if the transfer is significant, a requirement that a few metal wires cannot full-fill.

### 4.2.2 Metal Hydrides

Another group of fuel additives are metal hydrides. Typical hydrides are Aluminum hydride (AlH$_3$), Magnesium hydride (MgH$_2$), Lithium borohydride (LiBH$_4$) and Lithium aluminum hydride (LiAlH$_4$) [33, 43–45]. Hydride is the the anion of hydrogen. These metal-hydride compounds combine several performance enhancing mechanisms in themselves [43, 44]:

1. The hydrides serve as hydrogen depot (between 5 and 15 wt-%). During thermal decomposition, the hydrides release the stored hydrogen endothermically. Moreover, the hydrogen that is released can possibly augment the combustion itself.
2. The remaining metal component basically acts like a pure metal additive: They can combust and provide improved radiative heat transfer, leading to increased regression rates.

At this point, it is stressed again that the motivation of hydride additives is not primarily to increase the regression rate itself; the combination of higher flame temperature, more energy release and better radiation increases the regression rate as a consequence [33]. Nonetheless, as an example, DeLuca et al. [45] increased the regression rate of a HTPB/oxygen HRE up to 150% compared to the base case, using 11.2% AlH$_3$ addition.

On the contrary, mainly two aspects of metal hydrides are hindering wide usage of them for rocket propulsion. The first, very practical reason is the high cost and low availability of several metal hydrides. The best example is AlH$_3$ (also referred to as alane), which proved to have the highest performance impact of the hydrides but is poorly available in the western hemisphere. MgH$_2$, while readily available, is very expensive [33, 46]. The second reason for hydrides being not yet in use in commercial rocket propulsion are the major downsides like decreased shelf-life, spontaneous dehydrogenation and the general instability of hydride compounds [44, 45, 47]. Nonetheless, the significant performance increments that hydrides could provide drive the research efforts in this area.

### 4.2.3 Carbon-Based Additives

Carbon-based additives can also increase the regression rate. If carbon is added in the form of carbon black powder, it acts as an opacifying agent. This leads to an augmented absorptivity, meaning that the radiative heat transfer from the flame increases the surface temperature [48]. This, as a result, can increase the regression rate. As an example, Carmicino et al. [48] observed that a 3 wt-% carbon black addition in a GOX/HTPB motor enhanced the regression rate by 7% for higher mass-fluxes (130 kg/m$^2$s) and even 30% for lower mass-fluxes (90 kg/m$^2$s). Similar effects (even if not in the same order of magnitude) have been the result for Evans et al. [49] and Galfetti et al. [50]. However, as compared
to metal additives, the sole effect of carbon black on the regression rate is rather low. Nonetheless, carbon black in paraffin wax has shown in some case to decrease the thermal stability, thus leading to a 50% decrease of activation energy while exhibiting smoother combustion [51]. It is to be noted that an increased wear on the graphite nozzle throat was reported [52].

Another type of carbon-based additives are carbon nanotubes. These tubes promote the heat conductivity if inserted in HTPB grains, hence, increasing the regression rate [53]. Chen et al. [53] showed that the addition of 1% nano-tubes increased the regression rate by up to 31.6%. Interestingly, above 1% addition, the regression rate decreased (e.g., −39.7% at 3% nano-tube addition). Among others, agglomeration on the surface and high viscosity of the melting layer were traced back as source of the decreased regression rate effect [53].

Relating to the increased heat transfer to the fuel, another approach is expandable graphite as additive [54, 55]. The graphite particles (100–400 μm) expand at higher temperatures, forming strings that promote heat conduction into the fuel, by also expanding from the fuel surface into the flow. Elanjickal and Gany [54] investigated the effect of a 5% graphite addition to both polyester and paraffin as fuel with GOX. In the case of polyester, the regression rate increased by 100–200%; whereas in the case of paraffin, the increase amounted only to 30–50% (in both cases, low mass-fluxes exhibited higher percentage gains). The authors concluded that in the case of paraffin, the heat conduction (the characteristic that is promoted and affected by expendable graphite) plays a lesser role on the regression rate as the mechanisms (low melt temperature and entrainment) inherent to paraffin. For this reason, the relative increase of regression rate is smaller for paraffin [54].

### 4.2.4 Solid Oxidizer Particles and Energetic Binders

Another possibility to increase the regression rate is to insert solid oxidizer particles into the fuel. Examples are ammonium perchlorate (AP) 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 catalyst [56]. 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) [21]. Wada et al. [57] compared the regression rates of pure, inert PEG (Polyethylene glycol) with mixtures of PEG and the energetic GAP and observed significantly increased regression rates, approximately 264–285%. Nonetheless, using energetic binders comes with the same downsides as solid oxidizer additives, namely the loss of fuel inertness.

#### 4.2.5 Environmental Considerations for Fuel Additives

An important consideration for metallic and non-metallic additives is the impact on the climate change and ozone depletion [33]. Hybrids—in contrast to solids—do not release chlorine while burning (due to the absence of ammonium perchlorate in the fuel) [34]. This is an advantage, since chlorine is an ozone depleting compound [58, 59]. Nonetheless, adding metal additives leads to a release of alumina and other metal oxides, based on the type of metal additive. Depending on the mass fraction of the metal additive in hybrid rockets, the amount of oxides exhausted can reach values on par with classic solid rocket engines [34].

Unfortunately, literature on the quantitative impact of these metal oxides is lacking fundamental data. However, studies suggest that alumina expelled by rocket engines could produce considerable radiative forcing because it absorbs outgoing longwave radiation from the Earth [60]. This results in a warming effect on the Earth. Additionally, alumina particles can trigger reactions that have an ozone depleting effect [58]. Carbon black exhausted from fuels doped with carbon-based additives has a qualitatively similar effect on radiative forcing like alumina [60]. However, it is to keep in mind that hydrocarbon fuels (such as HTPB) already emit carbon black while burning, so that the additional effect of the doping is hard to quantify.

As for hydrides, the addition of hydrogen to the fuel (and consequently to the higher parts of the atmosphere) brings another aspects to consider to the equation. Hydrogen in the atmosphere favors ozone depleting reactions and generally leads to moisturizing of the atmosphere (when the H2 oxidizes to H2O) [61, 62]. Water vapor in the stratosphere is suspected to play a role in climate change [63] and the formation of mesospheric clouds, whose impact on the climate is not yet understood [58]. It is to be noted here that (as it is the case for carbon black) rocket launches in general exhaust H2O even without hydride additives. It is, therefore, difficult to assess the additional impact of the hydrogen released by the metal hydrides, but an important aspect to consider nonetheless.

### 5 Advanced Injection Methods and Designs

In the preceding sections, the chemical properties of the solid fuel grain were investigated. However, the oxidizer injection method also has a significant effect. The next sections discuss some of the existing designs and ideas.
5.1 Head-End Injection Methods

In the classical head-end injection, the oxidizer is injected at the entrance of the fuel port(s). 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. Carmicino and Sorge [64, 65] observed a dependency of the orifice to fuel port diameter ratio. They experimented with a conical axial injector for their studies with only one larger orifice. They noticed a strong relationship between the injector diameter (the oxidizer jet diameter at the entrance of the fuel port to be precise, see also Fig. 5) and the fuel port diameter. If both diameters are in the same order of magnitude, the flow in the HRE resembles a flow inside a pipe. However, if the injector orifice/jet is smaller than the fuel port, the oxidizer enters the chamber as a jet that impinges on the fuel inside the fuel port. Due to this, a recirculation zone is established which increases the heat transfer to the surface and the oxidizer transport and mixing. This effect is illustrated schematically in Fig. 5.

As a result, the authors observed regression rate increases by up to 150% and a more stable combustion [65]. To further assess the effect of the injection method, Carmicino and Sorge [65] also employed a radial injector head into the same motor which on the contrary resulted in higher pressure oscillations, slower regression rates and lower combustion efficiencies.

Bianchi, Nasuti and Carmicino [66] continued to investigate the effect of the port diameter for axial injection hybrids on the regression rate. They were able to separate the effect of the fuel port diameter into two regions. The orifice of the injector stayed constant at 8 mm for all tests. In the first region (below 30 mm port diameter), the injector effects are confined to the pre-combustion chamber; hence, the diameter has no influence on the regression rate. In fact, numerically, the regression rate decreases in this region slightly with increasing port diameter. Experimentally, this could not be observed due to limits in the regression rate measurement. Above 30 mm fuel port diameter, the regression rate increases with the port diameter, which is also precisely documented in the experiments. This is proving the described effects of Carmicino and Sorge [64, 65]. When the fuel port diameter is sufficiently large, the oxidizer jet impinges on the fuel surface and creates a recirculation zone that supports the regression rate enhancement (refer to Fig. 5). Likewise, Soller et al. [67] acknowledged the influence of the growing fuel port diameter on the injection flow characteristics. They proposed a so-called step-wise injection with two different orifice rows. Using this, it would be theoretically possible to alter the trajectory of the oxidizer and adopt it to the ever-changing fuel port geometry.

Bouziane et al. [68] also compared different injectors. The tested designs were showerhead (axial), hollow-cone (injects the oxidizer in a bi-directional fashion resulting in a hollow 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 case. Bellomo et al. [69] observed a similar trend for the vortex injection, where their experiments achieved a regression rate 51% higher with less instabilities. Further, Quadros and Lacava [70] obtained regression rates 2.4 times higher with a swirl injector than in a comparable axial injection scenario and with smoother combustion. These performance gains are explained with the elevated convective heat transfer due to the vorticity and elevated residence time of the oxidizer. The pressure-swirl case of Bouziane et al., however, had a 20% lower regression rate as their showerhead design. Interestingly, Bertoldi et al. [71] 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. In Japan, the swirl injection method was also being demonstrated in a small sounding rocket [72]. Burn tests reporting regression rates up to 2.7 times higher. The team surrounding the researchers continued on the swirl injection method (named SOFT: Swirling-Oxidizer-Flow-Type), continuously progressing the idea [73, 74] for a potential application in an economic hybrid launch vehicle for Japan [75].

Fig. 5 Impingement of oxidizer jet on fuel surface (based on [65])
The conclude this section, the last type of head-end injection methods are introduced: The Axial-Injection End-Burning—or AIEB—designs (not to confuse with the end-burning radial injection designs in Sect. 5.3). They are depicted in Fig. 6.

These concepts are being investigated at Hokkaido and Tokyo University since 1997 [76–79], by Hitt [80, 81] in cooperation with Frederick [82] and by Li et al. [83]. In these designs, the cylindrical fuel grain consists of many small canals with diameters of 0.3 mm [79] or 2–6 mm [83]. Alternatively, the fuel can be porous (e.g., porous High Density Polyethylene or HDPE [84]) with pore sizes of 15–200 μm [82]. Contrary to the classical HRE chamber, these fuel canals or pores do not serve as combustion chamber but rather as oxidizer feed line (typically GOX). The combustion itself in the AIEB takes place at the end of the fuel grain, not in the canals. The AIEB designs investigated present three major characteristics as compared to conventional HREs:

1. Because the fuel is burning at the end and not inside the canals, the burning surface stays constant with time, leading to a constant O/F ratio. Nagata et al. [79] observed neither a shift in O/F during nominal burn, nor during throttling, proving elevated throttle capabilities of AIEB type motors.

2. The volumetric loading achievable (due to the small ports/pores) is extraordinarily high. For example, with 0.3 mm port diameter and 2 mm spacing, the resulting volumetric loading is 98.1% [79]. However, the pore/port sizes and spacing displayed an influence on the regression rate. Generally speaking (with some exceptions during tests, which were explained with flame propagation back into the oxidizer ports [84]), the smaller the ports, the higher the regression rate [84]. Nonetheless, while this effect is being predicted analytically by Hitt and Frederick [82], due to the limited experimental data of AIEB test firings with different trends (e.g., Li et al. [83]), a definite answer to the effect of the diameter on the regression rate is still under investigation. For example, if the increasing port size also decreases the oxidizer velocity, the regression rate rises interestingly with increasing port/pore diameter [84].

3. The combustion behavior is fundamentally different from a classic HRE, which normally is largely independent from chamber pressure. In contrast, the AIEB-type HRE develops characteristics (including the pressure dependency) similar to solid rocket motors. In fact, the pressure exponent is higher as compared to solid rockets, approaching unity [78, 81]. At 12 bar chamber pressure, regression rates at least 9 times higher compared to HTPB references could be measured [82].

Problems like a high oxidizer pressure drop due to the thin oxidizer ports and complicated manufacturing of fuel grains with small port sizes are some of the problems yet to tackle for AIEB engines. The same applies for finding suitable fuel materials, especially for 3D-printing: Acrylonitrile Butadiene Styrene (ABS) and RapidNylon proved to be not ideally suited [84].

5.2 Distributed or Multi-Segment Injection

The aforementioned injection methods dominantly influence the regression rate at the head-end of the fuel port. To expand the influence of the injector, the method needs to be adjusted. Exemplary, two approaches are hereby introduced. The first is a continuation of the SOFT approach that was explained above, called the multi-section swirl injection method [75, 85–87]. The underlying idea is to inject the oxidizer not only at the head-end in a swirling motion but also through additional orifices further down along the axial length of the fuel grain (see Fig. 7).

This multi-section injection maintains a swirling oxidizer flow throughout the whole fuel grain rather than only at the head-end, leading to more uniform burning. It was tested both for HDPE and paraffin wax using GOX as oxidizer.
For the case of HDPE, the regression rate increased by about 100% compared to a HDPE non-swirling reference case [86]. The test with paraffin yielded regression rates 2–3.8 times higher compared to the paraffin baseline [75, 85]. The implementation of the sections (spacing, flow direction of the swirl, orifice size) shows a significant influence on the regression rate and needs to be thoroughly assessed. Numerically, the effectiveness of the multi-section injection was supported by Li et al. [88]. They simulated a H₂O₂/PE hybrid engine with varying sections of swirl injectors. Depending on the number of orifices and spacing between the sections, the simulations showed a regression rate 8.37 times higher than the non-swirl case and a combustion efficiency that increased from 86 to 95%. Vignesh and Kumar [89] compared the effect of swirl injection for only head-end and multi-section injection (here one additional swirl injector ring in the fuel grain). For the head-injection case only, the regression rate increase was only relevant for a 12 L/D motor (2.4 times increase), and small for a 24 L/D motor. The same trend was noted for the combustion efficiency. Hence, the authors concluded like their predecessors that high L/D engines could benefit from multi-section injection. Implementing a second injector ring inside the fuel grain, the regression rate could be increased by 100% compared to the showerhead base case for the 24 L/D motor. Interestingly, the direction of the swirl in the second injector ring did not influence the regression rate increase. Even more so, Vignesh and Kumar probed that it made almost no difference on the regression rate whether the second ring supplied oxygen flow or not. They concluded that the injector ring double-acted as mixing chamber and turbulence enhancing device, thus increasing the regression rate even without additional oxygen supply through the elevated heat transfer.

As a second example of distributed injection, two concepts that are similar are presented. The Beihang University [90, 91] and Kahraman et al. [92] propose another method to distribute the injector effects along the whole fuel grain rather than only at the head-end. The concept is labeled double tube by Beihang University and Distributed Tube Injector (DTI) by Kahraman et al. In both concepts, the oxidizer is injected by a tube over the whole fuel grain length. Yu et al. [91] use GOX/HDPE as propellants and the injector tube is covered by a small inner fuel grain. The design is presented in Fig. 8. Through holes in the inner fuel grain, the oxidizer flow is inserted into the outer fuel port. Experimentally, the regression rate increased approximately by a factor of two compared to the respective axial injection case [90].

With Kahraman et al., the tubular injector (not covered with fuel) is also inserted in the cylindrical paraffin fuel grain. Along the injector length, the oxidizer flow can be tailored to achieve maximum efficiency. Since the DTI is in the center of the fuel grain and, thus, subject to high combustion temperatures, the material choice was critical. The best performance (in terms of both cost and durability) yielded stainless steel with a nylon protective sleeve [92]. In experiments, using N₂O as oxidizer, the regression rate could be increased by 3.9 times as compared to the reference case with the motor with only head-end injection and in many cases the combustion efficiency increased too.

### 5.3 Aft-End Injection Methods

The previous sections made clear that a normal head-end injection, while being simple, can lose some performance potential for the motor. This observation led to the proposal of several aft-end injection HREs. The arguably most known aft-injection design is the bi-directional vortex engine of Knuth et al. [93, 94] (Fig. 9) that uses GOX and HTPB as propellants. Here, the oxidizer is inserted 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 600% higher than in comparable HREs have been reported, explicitly stating that a potential upper limited has neither been observed nor reached [94]. The authors explained the regression rate gains with elevated heat transfer due to the high-speed swirling motion and additional oxidizer attack on the fuel surface.
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(Visible at the aft-end injection area). Moreover, the oxidizer travels inside the fuel port two times (first upwards, then downwards), increasing turbulence and mixing. Observed fuel consumption was reported rather uniform and throttling and restart capabilities yielded satisfactory results. Interestingly, the regression rate showed a negative correlation with L/D, hence, favoring shorter and high diameter fuel ports.

A similar type of vortex HRE design is depicted in Fig. 10. It first occurred with Caravella et al. [95, 96], although they never published experimental data on the aft-end swirl injection design. Similar concepts were introduced by Haag et al. [97, 98], Rice et al. [99], by Lestrade et al. [100, 101], at Politecnico di Milano [102–106], by Jansen et al. [107] and in Japan [108, 109]. Usually, these engines are referred to as Vortex End-Burning Hybrid Engine (VEBH) or Vortex Flow Pancake (VFP) if two fuel discs are used; see Fig. 10a, b, respectively. Majdalani [110] developed in-depth analytical models for vortex hybrid rocket engines. Basically, this type of engine combines the characteristics of swirl injection with those of an end-burning engine: the regression rate and combustion efficiency increases and the fuel surface area stays constant, favoring a more consistent O/F. The reasons for increased regression rate and combustion efficiency are similar to other vortex/swirling designs, e.g., elevated heat transfer, improved mixing and residence time as well as reduced boundary layer height. Rice et al. [99] concluded from the post-firing fuel grain a counter-swirling vortex flow pattern, explaining the excellent performances of VEBH/VFP engines. An outstanding asset of VEBH and VFP is the compact design (L/D < 1 possible). This makes them particularly interesting for upper stages.

Quantitatively speaking, Hayashi and Sakurai [108] measured regression rates from 3.93 to 6.09 mm/s with paraffin and GOX. A typical paraffin/GOX axial engine (such as the 'original' from Karabeyoglu et al. [22]) only reaches regression rates from 0.6 to 0.8 mm/s in the concerned mass-flux range. This signifies an increase for the VEBH of 555–660% depending on the mass-flux. Hashish et al. [106] measured high combustion efficiencies up to 99%. To counteract the regressing fuel disk and avoid the combustion chamber size to decrease, active [108] and passive [101] actuators have been tested. This is supposed to keep injection location and the burning fuel surface close to each other to avoid combustion instabilities and ensure restartability (especially for catalytic ignition) [101].

However, especially the uneven burning pattern of the fuel discs raise concerns for high fuel slivers and changes in the engine’s behavior over time. Generally, the researchers observed significantly elevated regression rates at the fuel surface axis [99, 100, 108]. The common explanation of the high regression rate at the axis found is the high convection coefficient of vortex chambers as described by Volchkov et al. [111] in 1989. Another major concern for VEBH/VFP is the scalability. So far, only small mass-fluxes (with the exception of Lestrade et al. [100, 101] who tested up to 200 kg/m²s) and rather small engines have been investigated. For the sake of completeness, it is to be noted that the swirling ejection of the propellants through the nozzle could potentially lead to angular momentum of the whole spacecraft. Haag [98] measured the torque of his low thrust engine (under 100 N) on a test bench and concluded that the low thrust/low injection velocities of the engine would not lead to significant torque. Translated to a 100 kg cube-shaped satellite, the induced momentum would only lead to 0.14 daily revolutions. The potential problem of an angular momentum induced by the swirl for higher thrust engines is still to be evaluated and is also (to a lesser extent) shared with swirl/vortex head-end injection methods.

Fig. 10 a VEBH engine and b VFP engine

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6 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 in the sections below. Common approaches are advanced fuel port geometries or devices embedded in the fuel port to promote turbulence and mixing.

6.1 Multi-Port Designs

While pointing out that a multi-port design is rather mitigating the effects of a low regression rate than actually enhancing it [21], the increase of the burning surface due to multiple ports can counter the low regression rate problem. Multi-port solutions are a feasible approach to high thrust HRE applications. A prominent example is the 15-port fuel grain design of the record-breaking 1100 kN thrust HRE booster of AMROC [112]. Moreover, the usage of multi-port HREs can significantly decrease the L/D ratio, as already discussed in Sect. 3. For instance, Ahn et al. [113] were able to decrease the length of their HDPE/H₂O₂ HRE by increasing the port number to 14. Special caution during the design was given to avoid merging of the ports during burning. The shortened length and lower pressure oscillations again proved that multi-port approaches—while not increasing the regression rate—are possible counteracting solutions. It is to be noted though that an increasing number of ports can pronounce the problem of feed-coupling instabilities [114, 115]. Moreover, with port number also manufacturing costs increase and the system gets more complex. Together with high residuals and concerns about the structural integrity at advanced burn times, these characteristics are counted to the disadvantages of multi-port solutions [21].

6.2 Turbulence and Heat Transfer Enhancing Devices

In the previous sections on injection methods, it became clear that turbulence, heat transfer and enhanced mixing play a major role on the regression rate. These effects cannot only be achieved by advanced injection methods and designs but also by additions and adjustments inside the fuel port. The most straightforward approach are diaphragms (sometimes referred to as protrusion) in the fuel port. These diaphragms act as an obstacle inside the fuel port that creates turbulence and forms a recirculation zone behind the diaphragm. Figure 11 shows an exemplary HRE with a diaphragm.

A single diaphragm halfway into the fuel grain was observed to increase the total regression rate by 47% [116] or even 90% (numerically) if only the portion downstream the diaphragm is concerned [117]. The shape and height of the diaphragm influences the effect of the regression rate. Grosse [118] showed experimentally with N₂O/paraffin that a one-hole diaphragm at 33% of the total fuel grain length (x/L = 0.33) resulted in a 40% increase of regression rate downstream the diaphragm. Moving to a 4-hole diaphragm at the same position increased the regression rate by 84% as compared to the paraffin base case. The combustion (c-star) efficiency increased from the base of 86.7–93.7% and 96.6% for the 1-hole and 4-hole diaphragm, respectively. As for the diaphragm height, Moon et al. [116] tested different diaphragm height configurations in the middle of the fuel port. Changing the effective diaphragm height (the actual height that is reaching inside the oxidizer flow) from 2.5 to 5 mm increased the regression rate by 27% and 47%, respectively. Meaning a higher diaphragm leads to a higher regression rate increment. However, pressure oscillations of about 40% of the mean chamber pressure were observed. The authors concluded that this oscillation is induced by the edge-tone phenomenon (the impingement and deflection of the flow at the sharp diaphragm edge provoking pressure oscillations) [116, 119, 120].

The different investigations on diaphragms have in common that the effect on the regression rate seems to be limited to downstream of the diaphragm. Additionally, the influence of the diaphragm on the regression rate is in correlation with the recirculation zone length induced by the diaphragm [117, 119]. For this reason, the effect of multiple diaphragms along the fuel grain length has been also a field of interest. Kumar and Kumar [121] simulated different diaphragm diameters and their optimal spacing. Based on the results, they concluded that the ideal spacing of the diaphragms has to be slightly higher than the recirculation zone they induce. Quantitatively speaking, the optimal spacing was calculated to be 8–10 times the diaphragm height. Further, the simulation showed that few tall diaphragms (7 mm height) are increasing the regression rate more than multiple smaller diaphragms. Ideally spaced, the 7 mm diaphragms led to regression rate increases of 240% for a mass-flux of...
500 kg/m²s. It is to be noted that the pressure drop inside the combustion chamber in this case was 30%.

Experimentally, Dinesh and Kumar [122] observed a similar trend, but the numbers varied, also because the diaphragms were made from nylon and, thus, regressed with the burn time. To ideally space multiple diaphragms, the reference was also the recirculation zone length. However, Dinesh and Kumar state that the spacing has to be at least 2.7 times higher than the recirculation zone length. For the height, 7 mm (in a fuel grain of 50 mm outer diameter) seemed to be the optimum, with smaller or larger diaphragms decreasing the regression rate enhancing effect. Nonetheless, three protrusions/diaphragms positioned at 0.2, 0.5 and 0.8 \(x/L\) increased the regression rate across all mass-fluxes by about 30%. A single diaphragm in the middle of the fuel grain only yielded around 10% regression rate increment, proving the benefits of multi-protrusion [122].

Evidently, diaphragms are not the only possibility to increase turbulence. As mentioned earlier, Lee et al. [119, 120] observed high pressure oscillations when using a diaphragm. This inspired them to use a backwards facing step instead of a diaphragm in the middle of the fuel grain. The implementation is rather simple. The fuel grain is separated into two halves, the first half having a smaller diameter than the second, hence, creating a step (Kamps et al. [123] are using a similar approach to enhance mixing). A diameter difference of 10 and 15 mm between the two halves increased the regression rate downstream the step by 28% and 50%, respectively [119]. Moreover, the pressure oscillation was measured to be only about 4% of the chamber mean pressure [120]. Kumar and Joshi [124]—instead of using only two different cylindrical fuel grains—utilized five fuel grain cylinders with two different inner diameters (25 mm and 35 mm). The grain parts were glued together (with alternating inner diameters) to create a stepped grain. In experimental firings, the regression rate proved to increase due to the turbulence and heat transfer enhancing effect, somewhere between 30 and 55% depending on the mass-flux. Earlier, a similar design with more, smaller steps was presented by Sakashi et al. [125]. Although they labeled it as a concave–convex design, in fact, the convex part represents the smaller fuel diameter and the convex part the larger diameter, effectively forming a lot of small, alternating steps (see Fig. 12).

The height of the steps varied between 3 and 9 mm and the width from 4.5 to 18 mm in a inner fuel port diameter of 90 mm. Quantitatively speaking, the regression rate compared to the cylindrical base case of the GOX/polypropylene motor increased by a factor of 1.7–2.0 due to improved mixing, larger surface area and augmented turbulent transport. The authors noted that the depth of the steps has a higher impact on the regression rate than the width of the steps, therefore a small width and high depth design would yield the best results concerning the regression rate. Interestingly, the c-star efficiency tends to drop slightly compared to the cylindrical design; and the effect of the steps on the regression rate decreases with the total fuel length. The authors recorded pressure oscillations (around 1% of the pressure with a frequency of 124–140 Hz) that they traced back to Helmholtz resonance effects [125].

Kumar and Ramakrishna [126] inserted a (hemispherical) bluff body at the head-end of an HRE, in front of the injector, as depicted in Fig. 13. The hemisphere alters the flow in two major ways. First, the oxidizer flow is ‘pushed’ to the fuel surface, where a small, strong recirculation zone is formed. Second, behind the body, another recirculation zone is formed. These two effects lead to a significantly higher oxidizer mass-flux directly at the surface, as compared to the case without a bluff body. This trend of higher mass-flux at the fuel surface has been observed to continue up until around 60% of the fuel grain length. The result is a regression rate increase of 100% for a GOX of 150 kg/m²s and 300% for 30 kg/m²s. Because the effect of the bluff body is limited in its influence of the flow downstream, the authors noticed the effect of the regression rate enhancement decreased with increasing \(L/D\). Nonetheless, the solid fuel consumption was more evenly than in a no bluff body.
case and the O/F remained more constant during the burn. Moreover, even changing the initial port diameter from 15 to 60 mm, the regression rate enhancement effect of the bluff body remained intact [126].

6.3 Advanced Fuel Port Profiles and Combustion Chambers

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 [127]. A recent review of the state of the art and challenges of additive manufacturing for hybrid rockets can be found in [128]. As an example, Hijkema [129] 3D-printed a fuel port profile that was optimized by a genetic algorithm to minimize O/F shift. Theoretically, the algorithm can be altered to optimize the performance based on many criteria, like for instance an optimum O/F, fewer residuals or possibly higher regression rates. He observed improved performance compared to the baseline tests and a reduced O/F shift as anticipated [129].

Instead of printing the fuel itself, it is also feasible to print the mold of the fuel grain around which the fuel (HTPB) is casted [130]. After casting, the mold, whose material is polyvinyl alcohol, can be dissolved in water, leaving only the fuel grain with the desired and complex port geometry. This method can potentially help to create complex fuel port geometries even with fuels that cannot be 3D-printed. Lee et al. [131], Fuller et al. [127] and Whitmore et al. [114] 3D-printed helical port structures that force the oxidizer to follow a helical path. The combined effect of increased skin friction coefficients (based on the model of flow in curved pipes of Mishra and Gupta [132]) and the centrifugal forces suppressing the wall blowing effect led to regression rate increases of up to 300% for very aggressive helices. Nonetheless, even the more modest helical designs were able to increase the regression rate by factors of two [114].

A novel interesting combustion chamber design (strictly speaking the fuel ports itself remain classic cylindrical) from Hokkaido University was first proposed in 1998 led by Nagata et al. [133]. It was named CAMUI (Cascaded Multistage Impinging-Jet) and is investigated up until this date, including flight heritage and scale-ups to 40 kN [134–141]. The CAMUI engine (typically using LOX/PE) consists of multiple fuel blocks with two fuel ports each. Multiple fuel blocks (up to 14 for the 40 kN variant [141]) are combined axially in a single engine. They are separated by smaller fuel spacers and the fuel grain is rotated by 90° from one segment to another (refer to Fig. 14).

The combined effect of the rotated grain and the spacing between the fuel blocks has a positive influence on the mixing, turbulence and, thus, the regression rate. This is mainly because of the hot combustion gases repeatedly impinging on the front fuel surfaces. Generally, the regression rate of the CAMUI engine is described by three different regression rate models, one each for (a) the upstream face of the fuel grain, (b) the fuel port and (c) the downstream face of the block. For each area, the respective regression rate is typically higher than a single port engine [140]. The most straightforward description is the regression rate inside the fuel ports, which showed to be described by the classical Marxman regression rate model. Nobuhara et al. [140] compared the regression rate inside the fuel ports of a N2O CAMUI engine to a similar single port engine and measured a regression rate increase of 100–115% depending on the mass-flux (O/F fixed to 7.7). For the upstream face, the regression rate is dominated by the flow impinging on the face, rather than the classical diffusion limited theory. The downstream face regression rate, on the other hand, is the most complex to understand, but has shown to be affected by impingement and propellant flow parallel to the end face. This leads to a rather non-uniform regression rate pattern [141]. Interestingly, two burning surfaces of CAMUI do show different burning behavior, namely the very first (front) face and the very last (downstream) face [139]. The first front face of the engine is not impinged by hot combustion gases but mostly by pure oxygen. This leads to a non-negligible chemical reaction contribution, additionally to the diffusion (convection) limited description. On the other hand, the last downstream face exhibits lower turbulence, because it is the last block and the small space between the fuel blocks is non-present. Due to the decreased turbulence, radiation effects on the regression rate have to be considered [139].

Summarizing, the CAMUI design allows for lower L/D for desired thrusts and better regression rate performance and
combustion efficiencies, but may suffer from residuals and structural integrity, to name two downsides.

Exploiting a similar effect of numerous fuel segments with multiple ports that are rotated relative to each other, Tian et al. [142, 143] presented a multi segmented grain. In this concept, neither the relative angular displacement nor the number of fuel ports for each segment is fixed. Likewise to CAMUI, between each segment, there is a small space to promote mixing and turbulence, as can be seen in Fig. 15. Experiments (H₂O₂/PE) with the smallest configuration (first fuel block has one fuel port, second fuel block has three ports) yielded a total regression rate increment of around 13% and the combustion efficiency increased by around 10% [142]. More detailed, the regression rate in the first block (a classic cylindrical fuel) did not change, while the second block experienced regression rates around 20% higher.

Numerically, the effect of number of ports, segments, grain length and rotation has been researched as a continuation [143]. The main element for efficiency for this type of engine has been identified as the rotation angle between the fuel ports of the segments. This angular displacement induces swirl, turbulence and enhanced mixing in the space between the segments. Quantitatively, a 30° angle between the fuel segments is the most efficient in terms of regression rate enhancement (up to 45.1%) and combustion efficiency increased by around 10% [142]. More detailed, the regression rate in the first block (a classic cylindrical fuel) did not change, while the second block experienced regression rates around 20% higher.

The Impact of Regression Rate Enhancement on Nozzle Erosion

Like most SRMs, HREs mainly use ablatively cooled graphite nozzles. Their nozzle throat erosion can be affected by the presented regression rate enhancement methods as a side effect. The field of nozzle erosion in HREs is relatively young, but very broad. This section gives a short understanding into the (side-) effects that regression rate enhancing designs and methods can have on the nozzle throat erosion. Generally, nozzle erosion in HREs is about 1.5 times higher [144] than for aluminized SRMs due to higher mass fractions of oxidizing species in HRE operations. Water vapor, for example, accounts for approximately 50% of the total nozzle ablation [144]. Nozzle erosion, especially in long burning applications, decreases chamber pressure and specific impulses of rocket engines [144, 145]. This is why it is important to also consider possible effects of the regression rate enhancing methods on the throat erosion. They can be both positive (rare) and negative (more commonly). The following aspects of regression rate enhancing designs affecting graphite nozzle erosion need to be considered:

Mixture Ratio

As shown in this article, regression rate enhancing ideas can alter the O/F of an HRE in both directions, either by default or during operation. The nozzle erosion typically peaks at the stoichiometric ratio and is lower at oxidizer or fuel-rich conditions, manly due to the decrease of flame temperature (see also next point) [146]. It is to be noted that the effect is significantly more pronounced for fuel-rich conditions, meaning that fuel-rich operated HREs benefit the most from the decreased nozzle erosion (around 60% lower erosion). For oxidizer-rich conditions, the effect is still present (6% reduction of erosion) but smaller [144]. The reason for this is that for oxygen-rich conditions, the molecular oxygen in the combustion gases are more dominant. Although the flame temperature is lower in these conditions, the oxygen reacts with the graphite and therefore heat is released. Quantitatively speaking, Bianchi and Nasuti [144] have shown that although the flame temperature at oxidizer-rich conditions decreased by 280 K, the nozzle throat temperature increased by 70 K as compared to a stoichiometric case.

Flame Temperature

Several energetic fuel additives can increase the flame temperature (recalling Sect. 4.2). While this is beneficial for the regression rate, it also increases the nozzle erosion considerably because the nozzle wall temperature augments also. Moreover, higher temperatures promote the production
of OH* an O* radicals that react with the graphite of the nozzle [144].

**Combustion Efficiency**

Several regression rate enhancing concepts increase the mixing and combustion efficiency as a side effect. For the nozzle, however, increased efficiency and mixing augment the throat erosion [144, 146, 147]. This is due to several phenomena. Firstly, increased combustion efficiency increments also the flame temperature. As stated above, higher flame temperatures increase the nozzle erosion. Moreover, the fractions of the combustion products (and therefore oxidizing species) change due to increased efficiency. It is to be noted that HREs with relatively low efficiency often form a protective fuel film over the nozzle throat due to the poor mixing. When the mixing is increased, the film diminishes, effectively increasing nozzle erosion [147].

**Reducing the Oxidizing Species of the Flow**

Additives such as aluminum (Al), have shown to decrease the erosion by 45% [145]. This effect has been partly traced back to the fact that the aluminum reacts to aluminum oxide (Al₂O₃), effectively reducing the concentration of oxidizing species at the nozzle throat. The second effect is that a liquid Al₂O₃ film is formed that protects the nozzle graphite [145]. However, as stated in Sect. 4.2.1, these metal additives can agglomerate and impinge on the nozzle, therefore increasing the wear on the nozzle [21, 36].

Summarizing this section, it becomes evident that the different regression rate enhancing ideas can have a non-negligible effect on the nozzle erosion. The O/F plays (among chamber pressure) the most prominent role for the nozzle erosion [144]. A complete investigation of the complex physical phenomena their interactions are out of the scope for this article. Nonetheless, the possible negative (and in rarer cases positive) side effects of regression rate enhancement on the nozzle erosion needs to be considered when choosing or developing a regression rate enhancing concept. However, it is to be stressed that the overall goal is to increase the performance of HREs. Possible negative side effects on the nozzle erosion should not limit the development of regression rate enhancing concepts. The side effects on nozzle erosion can be countered with novel solutions. These techniques use either regeneratively cooled systems (which is very delicate with liquid oxidizers [145]), or different materials and mitigation approaches. As an example, Narsai [147] proposes to place a small fuel sliver directly upstream the nozzle to deliberately trigger a cooling fuel film. Similarly, Karakas et al. [145] glued a ring of aluminum-doped paraffin at the front of the pure paraffin fuel, creating a cooling film that decreased erosion by more than 40%.

### 8 Comparative Overview of Techniques and Designs

In the previous sections, numerous designs and their effects on the regression rate have been presented and discussed. This allows to compare those designs in a more illustrative way now. From this point on, we will only regard experimentally tested engines and data, while numerical simulations (although being a powerful tool) are not considered

![Fig. 16 Average regression rate of GOX and non-liquefiable fuel combinations](image-url)
The first comparison to draw is the space-time averaged regression rate over oxidizer mass-flux of selected designs that have been discussed previously. This regression rate fit is based on the classical diffusion limited regression rate model developed by Marxman et al. [11, 148]. The space-time averaged description of the regression rate denotes to:

\[
\dot{r} = a \cdot G_{ox}^n,
\]

where \(G_{ox}\) is the oxidizer mass-flux \([\text{kg/m}^2\text{s}]\), \(\dot{r}\) the regression rate in \(\text{mm/s}\) and \(a\) and \(n\) are constants that are depending on influences such as propellant choice, geometry and injection. They can be experimentally determined and, therefore, allow comparing different HREs and designs; keeping in mind that Eq. 1 utilizes a number of simplifications and

| Name                     | Propellants                | \(a\) | \(n\) | \(G_{ox} [\text{kg/m}^2\text{s}]\) | References |
|--------------------------|----------------------------|-------|-------|----------------------------------|------------|
| Paraffin base            | Paraffin/GOX               | 0.091 | 0.69  | 20–110                           | [22]       |
| HTPB base                | HTPB/GOX                   | 0.0903| 0.527 | 62–310                           | [149]      |
| HDPE base                | HDPE/GOX                   | 0.0419| 0.498 | 77–261                           | [149]      |
| Multi section swirl      | PVC/GOX                    | 0.1418| 0.51  | 56–240                           | [89]       |
| Double tube              | HDPE/GOX                   | 0.0697| 0.561 | 24.7–44                          | [90]       |
| Bi vortex\(^a\)          | HTPB/GOX                   | 0.193 | 0.54  | 7.41–121.8                       | [94]       |
| End-burn swirl (H)\(^a\) | HTPB/GOX                   | 0.4   | 0.68  | 2–4                              | [99]       |
| Single step\(^b\)        | HDPE/GOX                   | 0.0432| 0.53  | 30–90                            | [119]      |
| Single diaphragm\(^b\)   | HDPE/GOX                   | 0.0585| 0.53  | 30–90                            | [119]      |
| CAMUI port               | PE/LOX                     | 0.024 | 0.8   | 250–700                          | [136]      |
| AP + Ferric oxide\(^c\)  | HTPB/GOX                   | 1.1065| 0.259 | 70–281                           | [56]       |
| End-burn swirl (P)        | Paraffin/GOX               | 0.3825| 0.8506| 15.8–26.1                        | [108]      |
| Nested helix             | Paraffin/ABS/GOX           | 0.1746| 0.43  | 10–40                            | [29]       |
| Diaphragm (1 hole)       | Paraffin/N\(_2\)O         | 0.5387| 0.36  | 100–250                          | [118]      |
| Diaphragm (4 hole)       | Paraffin/N\(_2\)O         | 0.2934| 0.518 | 100–200                          | [118]      |
| Bluff body               | Paraffin/GOX               | 0.836 | 0.4   | 30–150                           | [126]      |
| Head end swirl           | Paraffin/GOX               | 0.496 | 0.62  | 15–32                            | [70]       |

\(^a\) and \(^b\) values from [13].

\(^c\) Values extracted from images in reference

\(^c\) For 350 psi pressure.
assumptions, which do not necessarily encompass all physical phenomena in an HRE. Nonetheless, from an engineering point of view, this simplified equation is largely sufficient. For a deeper understanding and the different nuances of the diffusion limited model the reader is referred to Marquardt and Majdalani [12].

In Figs. 16 and 17, the average regression rate model for selected designs is plotted according to Eq. 1. For better overview, the data are split up in in two different images, and not all designs that have been discussed in this article are presented. Figure 16 shows the data of non-liquefiable fuels (HDPE, PVC, HTPB); Fig. 17 basically illustrates the same information but for designs with liquefiable fuels (mostly paraffin). The baseline cases without any regression rate enhancement (namely HDPE, HTPB and Paraffin) are represented in both figures. The oxidizer in all cases (except for the diaphragms of Grosse [118]) is oxygen, to promote comparability. The data for the propellants, mass-flux ranges, \( a \) and \( n \) values and the concerning references presented in Figs. 16 and 17 are summarized in Table 3.

Looking at Fig. 16, the most striking observation is that out of the selected non-liquefiable designs there are three that even beat the regression rate of the paraffin base case. This is, of course, assuming the regression rate models are also valid outside their tested mass-flux range. These designs are namely the end-burn swirl (H for HTPB) of Rice et al. [99], the bi-vortex engine of Knuth et al. [94] and the HTPB/AP/ferric oxide blend of Frederick et al. [56].

This proves once more the influence different designs and techniques can have on the regression rate. It is to be noted that for example the design of Rice et al. was only tested for very low mass-fluxes but it is questionable if the same trend is applicable for high mass-fluxes. However, it can serve as a strong indicator for the capability of end-burn engines. For the AP/ferric oxide case of Frederick et al., the regression rate increase is immense, but at the cost of the fuel inertness as explained in Sect. 4.2.4.

These examples are rather big adjustments to a classical hybrid engine. Nonetheless, already for small adjustments (single steps, diaphragms), the impact on the regression rate is observable, even if less pronounced. This leads to the conclusion that enhancing the regression rate is a delicate trade-off problem. Complex (end-burn, bi-vortex) or non-inert (ferric oxide/AP) designs dramatically increase the regression rate, but introduce new downsides to the hybrid engine design. On the other hand, small adjustments to the design introduce less problems, but also have limited enhancing effects.

This trend is also observable for the liquefiable fuels in Fig. 17. Almost all displayed designs and techniques increase the regression rate significantly as compared to the paraffin base. The diaphragms of Grosse [118] are only

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**Fig. 18** Regression rate increment as compared to the respective reference case. Entries with * compared to a equivalent motor from literature, not their own
smaller adjustments that have a noticeable impact on the regression rate. However, more complex designs such as the end-burning swirl engine (P for Paraffin) in Hayashi and Sakurai [108] show immense increment. A noteworthy exception displayed in Fig. 17 is the bluff body of Kumar and Ramakrishna [126]. It is a relative straightforward approach but the increment is considerably high.

Figures 16 and 17 compared the average regression rates of different designs among each other. While the regression rate fit is a very powerful tool of comparison, it could distort some of the results because of simplifications to the model. The $a$ and $n$ values depend to some extent also on the engine design, geometry and its operating conditions. For this reason, it is necessary to take Fig. 18 into account. Here, the different designs and techniques with their relative regression rate gain in percent are listed. Contrary to Figs. 16 and 17, however, the percentage is referring to the unique reference case of each author without the regression rate enhancement technique. For example, in the 140% increase of the swirl injection [70], the authors tested the engine with and without swirl injection under the same conditions (e.g., propellants, geometry) on the same motor, allowing to single out the effect each enhancing idea has on the specific engine. It is a powerful way to quantify the potential of each concept individually. It is to be noted that the values of Fig. 18 are only valid for each specific motor. It is not guaranteed that the percentage can be translated to every other engine (i.e., quantitatively a diaphragm can have different effects depending on the motor). Nonetheless, Fig. 18 gives a profound understanding on how much each concept was able to increase the regression rate of the respective motor.

The bi-vortex engine of Knuth et al. [94] and the AIEB design of Hitt and Frederick [82] show by far the highest regression rate increase. For the AIEB, the values have to be regarded with caution, as the high pressure dependency of AIEB designs makes it difficult to compare directly with classic hybrid combustion phenomena. Nonetheless, the potential of AIEB is enormous. Noteworthy are the high values of DTI, bluff body and helical grain designs. These are rather simple adjustments to the overall HRE (for helical grains this depends a lot on the progress of additive manufacturing) with significant regression rate enhancement of 290–300%. Diaphragms and steps are to be found somewhere in the middle, and their impact on the regression rate increases with the number of steps.

Figure 18, while being very informative, can serve another purpose. As pointed out in the beginning, the different regression rate enhancing ideas are not necessarily exclusive. Meaning that—in theory—one or more different techniques can be combined in a single design. For the paraffin designs presented in Fig. 17, this already was achieved, given that a liquefiable fuel with, e.g., swirl injection technically combines two regression rate enhancing ideas. The overview of Fig. 18 can serve as an inspiration for different combinations and allows for a first (very rough) estimation on possible regression rate enhancement. For example, a combination of diaphragm, swirl and AP additive was numerically investigated, first individually, then together [150, 151]. The authors observed that the regression rate enhancements do complement each other, leading to higher total regression rates. Nonetheless, the individual regression rates did not add up arithmetically. The sum of all individual techniques would yield 390%. However, in the simulations, the authors observed a combined value of 345% higher regression rate as compared to the base case [150].

Concluding, the hybrid rocket research all around the world led to very promising and clever ideas to increase the regression rate. While some of the designs are based on significant changes to the design, others are only minor adjustments. With the help of Figs. 16, 17 and 18, these ideas can be assessed and possibly serve as inspiration for new or combined ideas.

9 Concluding Remarks

In this article, several techniques to augment the regression rate of HREs were presented and the mechanisms driving the enhancement explained. It 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. The methods have been combined into three major groups, namely chemical methods (additives and liquefiable fuels), advanced injection methods and lastly alternative combustion chamber designs. The different research efforts were presented and their impact on the regression rate and the accompanying disadvantages discussed. In our view, 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. Moreover, these minor adjustments could in theory be combined in a single motor to further increase the regression rate.

Finally, an important consideration needs to be addressed. As elaborated in Sect. 8, the regression rate enhancement can be considered as a trade-off problem. For example, complex designs such as the multi-section swirl or the bi-vortex engine can significantly increase the regression rate, but could potentially add weight and complexity to the engine. Moreover, the group of energetic binders and solid oxidizer
particles sabotages some of the hybrid rocket engine’s unique advantages; namely the safety and easy handling. It is to be questioned if complex and expensive hybrid rocket engine designs with possibly non-inert fuel can still compete with solid or liquid rocket engines. We believe, in order for the hybrid rocket engine to be widely used in the space sector, their advantages (simplicity, flexibility and low-cost) need to be embraced.

### Appendix 1: Overview of Techniques Presented in the Article

See Table 4.

| Name                  | Description                                      | References | Section |
|-----------------------|--------------------------------------------------|------------|---------|
| Liquefiable fuels     | Liquid melt layer on fuel surface                | [22, 23]   | 4.1     |
| Armored grain         | Reinforcing structure in paraffin               | [27, 28]   | 4.1     |
| Nested helix          | Swirl inducing structure in paraffin             | [29]       | 4.1     |
| Aluminum additives    | Higher temperature and radiation                | [35, 36]   | 4.2.1   |
| Transition metal additive | Decrease thermal stability                        | [38, 39]   | 4.2.1   |
| Embedded metal wires  | Promote heat transfer to grain                   | [41, 42]   | 4.2.1   |
| Aluminum hydride      | Embedded energy depot                             | [45]       | 4.2.2   |
| Carbon black powder   | Opacifying agent                                  | [48–52]    | 4.2.3   |
| Carbon nano tubes     | Promote heat conductivity                         | [53]       | 4.2.3   |
| Expandable graphite   | Conductivity through expansion                   | [54, 55]   | 4.2.3   |
| AP + ferric oxide     | Catalyst                                          | [56]       | 4.2.4   |
| GAP                   | Energetic binder material                         | [57]       | 4.2.4   |
| Conical axial injection| Formation of recirculation zone                  | [64–66]    | 5.1     |
| Hollow-cone injector  | Bi-directional injection                          | [68, 71]   | 5.1     |
| Pressure-swirl injector| Annular sheet injection                           | [68, 71]   | 5.1     |
| Vortex injection      | Rotating injection                                | [68, 69, 71]| 5.1     |
| Swirl injection       | Swirl injection head-end                          | [70, 72, 74]| 5.1     |
| AIEB                  | Fuel port as feed line, end-burning              | [77–84]    | 5.1     |
| Multi section swirl   | Swirl injection along grain                       | [85–89]    | 5.2     |
| Double tube           | Injector tube inside fuel port                   | [90, 91]   | 5.2     |
| DTI                   | Injector tube inside fuel port                   | [92]       | 5.2     |
| Bi-vortex             | Induces counter-swirling vortexes                | [93, 94]   | 5.3     |
| VEBH/VFP              | End-burning vortex combustion                     | [95–110]   | 5.3     |
| Multi-port grain      | Increase burning surface                         | [112, 113] | 6.1     |
| Single diaphragm      | Induce turbulence and mixing                     | [116–120]  | 6.2     |
| Multiple diaphragms   | Induce turbulence and mixing                     | [121, 122] | 6.2     |
| Single step           | Induce turbulence and mixing                     | [119, 120, 123]| 6.2 |
| Multiple step         | Induce turbulence and mixing                     | [124]      | 6.2     |
| Concave-convex port   | Induce turbulence and mixing                     | [125]      | 6.2     |
| Bluff body            | Alter recirculation zones                        | [126]      | 6.2     |
| Genetic algorithm     | Optimized profile for low O/F shift              | [129]      | 6.3     |
| 3D-printed mold       | Complex port geometries                          | [130]      | 6.3     |
| Helical grain         | Increased friction coefficient                   | [114, 127, 131]| 6.3 |
| CAMUI                 | Impingement and mixing chamber                   | [133–141]  | 6.3     |
| Multi segmented grain | Impingement and mixing chamber                   | [142, 143] | 6.3     |
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Declarations

Conflict of interest

The authors declare that there is no conflict of interest.

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