Swirl Injection Effects on Hybrid Rocket Motors

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ABSTRACT: In the last decades, hybrid rocket engines have been increasingly studied and used in space vehicles. However, the low regression rates and specific impulses still represent major drawbacks to this technology. The objective of this study was to quantify the relative improvement of regression rate values with the use of a swirling flow injector in comparison to an axial injector. Seven tests were conducted with axial injection and seven with swirl injection. Regression rate results were compared, and it was found that swirl injection improved regression rates in 50% for mass fluxes higher than 45 kg·s⁻¹·m⁻². It was possible to see radiation, kinetic and diffusion theory on the logarithmic plot of regression rate per oxidizer flux yielded by both injectors. A strong agreement with experimental findings of regression rates in the literature parameters is reported.

KEYWORDS: Hybrid rocket motor, Swirl injector, Solid fuel regression rates.

INTRODUCTION

In the quest for a novel propulsion technology, the hybrid rocket engine draws attention due to features such as thrust tailoring and lower investment costs in comparison to solid motors and liquid engines (Pastrone 2012). Nevertheless, combustion inefficiencies and low regression rates are the major weaknesses of this technology. This research aims to contribute to the improvement of the regression rates with the use of swirl injectors.

The combustion in a hybrid motor follows a non-premixed pattern and visually is a macroscopic diffusion flame. The flame zone is established within the boundary layer, in which the solid fuel has to melt and vaporize or pyrolyze as well as mix with the oxidizer in the flame zone as shown in Fig. 1 (Marxman and Gilbert 1963). In this way, hybrid combustion phenomena differ from what occurs in liquid and solid motors, where the flame is pre-mixed and no relevant energy is spent mixing fuel and oxidizer.

The regression rate is a parameter defined to quantify the amount of fuel transferred from the solid grain into the flame zone. Thermal energy must be transferred to the solid fuel surface to change the physical phase, thus it follows that one of the most important parameters to improve regression rates is heat flux from the flame to the surface.

Right above the surface of the solid grain, a layer of melted or gasified fuel is formed; this layer is cooler than the flame and acts as a thermal isolator, hindering the heat transfer from the flame to the solid surface. This phenomenon is documented in the literature as blowing effect.

The regression rate depends primarily on the convective heat transfer from the flame to the fuel surface; hence the whole combustion process will be affected severely by
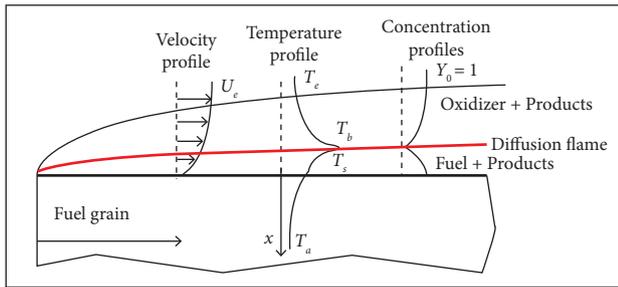
Figure 1. Boundary layer combustion mechanism in hybrid rocket chamber (Altman 2001).

the incoming oxidizer flow pattern as it alters the flow dynamics on the grain surface (Carmicino and Russo Sorge 2005a; Yuasa *et al.* 2012).

Given the importance of the regression rate improvement, several methodologies have been tested to increase this parameter. The literature confirms that swirl injection is one of the most efficient means to increase the regression rates of a given fuel (Pastrone 2012; Carmicino and Russo Sorge 2007; Knuth *et al.* 1998; Imamura *et al.* 1996).

Yuasa *et al.* (2001) tested swirl injectors at the grain head end and report results for different grain lengths, geometric turbulence factor and flow of oxidant. The intensity of rotation and oxidant mass flow were varied independently. Swirl GOX injection yielded 2.7 times greater regression rate than axial injection of polymethylmethacrylate (PMMA).

Another research shows that while the local fuel regression rate at the rear region decreased slightly with the increasing of the burning time, local regression at the leading edge was independent of burn time (Hirata *et al.* 2011). These results suggested that the combustion mechanisms at the leading edge and the rear region are differed (Hirata *et al.* 2011).

The injection effect, indeed, is expected to be more important when the extent of the impinging region is larger compared to the grain length (Carmicino and Russo Sorge 2005b). The high-velocity, swirling oxidizer near the fuel surface induced high convective heat fluxes, which sustained the large regression rates (Knuth *et al.* 2002).

Relevant work has been done in hybrid rocket simulation. Researchers were able to simulate the flow inside a hybrid rocket chamber with CFD and compared it to experimental results (Bellomo *et al.* 2011, 2013).

CFD investigations are now able to point out that swirl improves regression rate and combustion when compared to axial injector (Bellomo *et al.* 2011, 2013). Swirl injectors can

also be used with liquefying fuels; in such case paraffin fuel burns about twice as fast by swirling GOX (Hikone *et al.* 2010).

In accordance to Kumar and Kumar (2013), swirl is more effective in improving the average regression rate of short grains (total length over inner diameter, L/D < 5) and large diameters as opposed to longer grains. From the research of Kumar and Kumar (2013) and Carmicino and Russo Sorge (2005b), it follows that the swirl effect is more pronounced on short grains.

Another research captured the liquid layer on the surface of a high-density polyethylene grain burning with axial injector (Chandler *et al.* 2012). It is expected that polyethylene form a liquid layer, but due to the high viscosity, entrainment effect is unlikely. Nevertheless, they were able to visualize droplets above the fuel.

With visualization techniques, scientists were able to see that, when swirl injector is used, the flame is driven close to the surface, resulting in an increase of the regression rates. This happens due to the centrifugal force of the swirling flow of oxidizer (Masugi *et al.* 2010). Swirl effect is so noticeable that conventional combustion regression rate equation using the oxidizer mass flux based on the grain port area is not well applied, due to different flows in the rear and aft regions of the grain (Yuasa *et al.* 2012).

The present paper will discuss the regression rate improvements with the use of swirl injector in comparison to the results of the axial injector. This research was also able to verify the effects of radiation, kinetic and diffusion theory on the logarithmic plot of regression rate per oxidizer flux yielded by both injectors.

EXPERIMENTAL SETUP

The baseline engine design was developed from a need for simplicity and flexibility; therefore a modular design was incorporated. The set could be assembled and disassembled in minutes allowing the practice of many tests per session. The case and the flanges were made from stainless steel. The case was machined to fit between the steel flanges. The nozzle was adapted in the aft flange, to avoid nozzle exit during firings. A hydraulic system was settled to perform the thrust measurements. A schematic diagram of the test facility is exposed in Fig. 2.

The pressure was taken in the oxidizer feedline before the injector. The measurements were the feedline pressure, regression rates, oxygen and fuel mass before and after tests. The chamber was designed to withstand up to 70 atm.

Compression fitting valves were used in the oxygen feed line, in order to disengage if the pressure rises above 60 atm. A pyrotechnic method was used to achieve ignition. The chamber's length is 215 mm with an inner diameter of 68.3 mm. The grains are 195 mm long. The aft-chamber has a span of 15 mm and the pre-chamber is 5 mm long. Two injectors were developed, one axial and one swirl. A view of the motor attached to the test bench is shown in Fig. 3.

Figure 4 show different sides of the injectors. The easy interchange of injectors in the head flange and effortless alteration in the oxygen feed line due to the compression fit
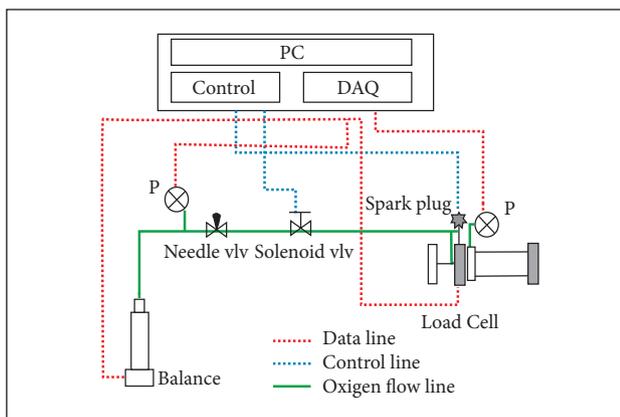

Figure 2. Diagram of the experimental apparatus. It is possible to see the data acquisition (DAQ); the control panel (PC), and the needle and solenoid valves (vlv).
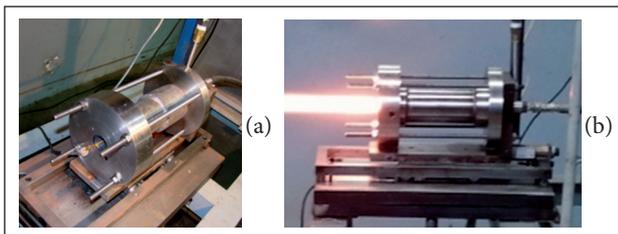

Figure 3. (a) Side view of the labscale hybrid rocket motor on the test bench. (b) Firing test.
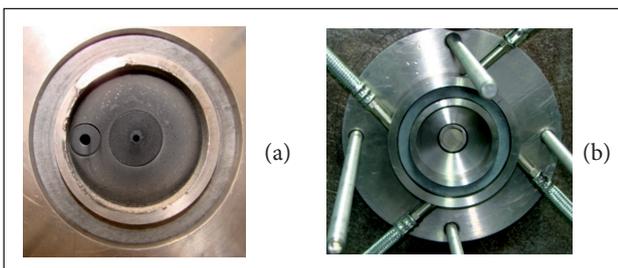

Figure 4. (a) Axial injector mounted on the test bench; (b) Large swirl attached to the test bench with the four oxidizer supply entrances.

valves connections contribute to the trouble-free experimental apparatus. Figure 4 display the injectors attached to the head flange of the test bench. Figure 4a shows two holes, one for the axial injector and the other for a pressure transducer, which was not functional at the time of the tests.

All injection exits and entrances are identical to guarantee homogeneous flow and regular burning along the port. The large injector outlet area works like an additional pre-chamber, enhancing the uniformity of the incoming flow conditions.

In the beginning of the research, the maximum pressure of injection was set at 40 atm; this is the pressure taken right before the flow enters the injector. This value was chosen to investigate the security of the apparatus and whether the hoses would release before the 60 atm chamber pressure limit. Once many tests were accomplished without failure or damage, the maximum injection pressure was gradually increased to 46, 52, and 58 atm.

In this manner, a total of 7 tests were done for each injector (4 with 40 atm and 3 with 46, 52, and 58 atm). The maximum injection pressure was set manually by an electron valve. The masses of the oxygen cylinder and of the case were taken before and after each test. The tests began with ignition using a pyrotechnic ignitor, also known as squib. Then, the flow of oxygen was switched on for 10 s; this was controlled with LabView. After the firing the inner diameter of the grain was measured in five different locations to calculate the average regression rates as will be explained in the next section.

RESULTS AND DISCUSSION

The key purpose of the regression rate analysis is to determine the correlation between regression rates and easily controlled parameters along with experimentally derived constants; in this work the average regression rate, as defined by Marxman and Gilbert (1963), is used, once it provides good correlations. Correlation patterns were determined by making scatter plots and applying correlation analysis to the cluster of data points provided by the test firings.

Average regression rate is defined in Eq. 1:

$$\dot{r}_{\mathrm{avg}} = a_0 \bar{G}_{\mathrm{ox}}^n \qquad (1)$$

where:

a_0 is the regression rate experimental coefficient incorporating grain length; $\overline{G}_{ox}$ means the average oxidizer mass flux rate; n is the experimental regression rate exponent.

Assuming a uniform inner diameter growth, the average oxidizer mass flux is experimentally defined as Eq. 2:

$$\overline{G}_{ox} = \frac{\dot{m}_{ox}}{\pi\left(\frac{D_i+D_f}{2}\right)^2} \qquad (2)$$

where:

D_i is the initial port diameter; D_f is the final port diameter; $\overline{\dot{m}}_{ox}$ is the average oxidizer mass flow rate.

Using experimental data, the average regression rate is calculated as follows:

$$\dot{r} = \frac{D_f-D_i}{\Delta t} \qquad (3)$$

where:

Δt is the burn time.

The initial port diameter of all grains is 20 mm. In this study, the final diameter is defined as the average value of the diameters of 5 cross-sections, as shown in Fig. 5.

Tables 1 and 2 present the regression rates and oxidizer flux of HDPE fuel with the use of axial and swirl injectors.
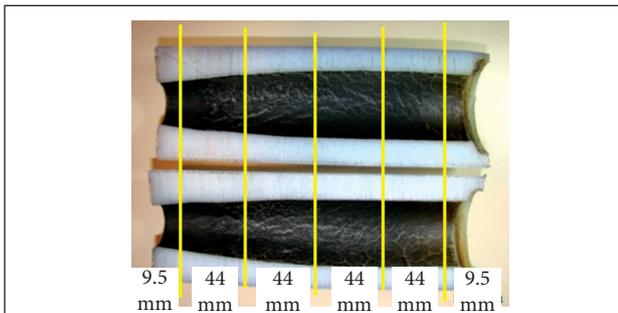

Figure 5. Cross-sections for the calculation of mean regression rate.

Table 1. Axial injector.

$\overline{Gox}$ [kg/sm²]	$\dot{r}$ [mm/s]
33.0	0.85
33.1	0.84
41.0	0.86
50.4	0.88
52.6	0.91
89.3	1.12
131.1	1.15

Tables 1 and 2 show that, when mass fluxes are smaller than 45 kg/sm², swirl regression rates are 25% higher than the values yielded by the axial injector. However, for mass fluxes higher than 45 kg/sm², the regression rates increase at least 50%, in respect to the values obtained with the axial injector.

Fuel regression rate yielded by axial and swirl injection methods is presented in Fig. 6. The analysis of Fig. 6 shows that, for the same mass flow of oxidant, the large rotational swirl yielded higher regression rates.

The diffusion-controlled model has two assumptions. The first is that the reaction rates are faster than the rates of the diffusion of the chemical species, and the second assumption refers to the thickness of the boundary layer, which is supposed to be orders of magnitude larger than the combustion zone thickness; this means that Eq. 1 works perfectly. Therefore the logarithms of regression rate and of mass flux form a line, the center line of Fig. 7. This theory can be further understood reading the original article by Marxman and Gilbert (1963).

It is observed that, at constant pressure, when the oxidizer mass flux decreases, the regression is likely to vary and depend on the radiation environment, becoming larger than the extrapolated values (Altman 2001; Marxman and Gilbert 1963).

This happens because in low oxidizer concentrations the burning is not complete, and species from the incomplete
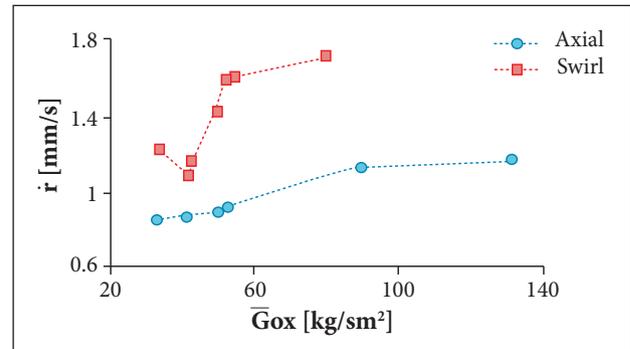

Figure 6. Regression rate *versus* oxidizer mass flux for each injection method.

Table 2. Swirl injector.

$\overline{Gox}$ [kg/sm²]	$\dot{r}$ [mm/s]
33.3	1.20614
41.9	1.07427
42.9	1.15134
49.5	1.4145
52.0	1.57644
54.8	1.59653
79.9	1.70432

combustion, such as carbon black, increase the radiative heat exchange, improving the regression rates. These results are consistent with other findings in the literature.

One study shows that thermal radiation was found to expressively influence the regression rates (Chiaverini *et al.* 2000). To quantify the importance of radiative heat flux, a study found that the difference of regression rate when single port and multiport are used is due to the radiative heat flux as the port number increases, and there are more species from incomplete combustion (Kim *et al.* 2013).

Differently, at high mass fluxes or low pressure, the hypothesis that reaction rates are higher than velocity of diffusion is not valid anymore. It is observed that the reactions become the slow stage of the burning process; this is why it is called kinetic dependent, and the values are lower than the extrapolation (Fig. 7).

Figure 8 shows the logarithm of the regression rate *versus* logarithm of oxidizer mass flux. It is clear that both curves follow the theory graphically presented in Fig. 7, once the middle section
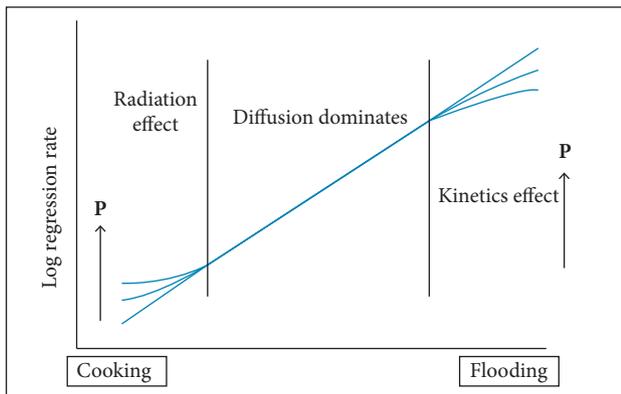

Figure 7. Diagram of the influence of radiation and kinetics effects on regression rates adapted from Altman (2001) and Pastrone (2012).
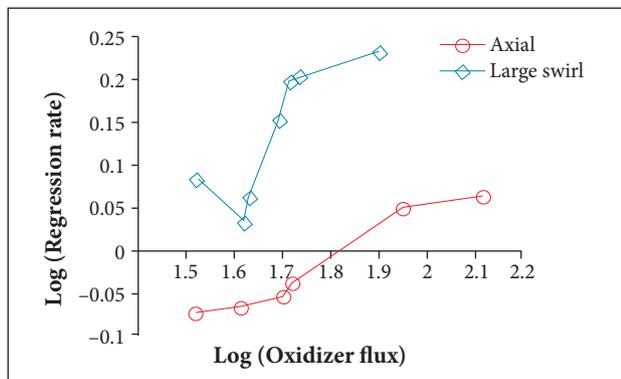

Figure 8. Scattered data with smooth lines.

is flat, low values of oxidizer flux yield higher regression rates than extrapolated and high values of oxidizer flux yield lower values than extrapolated. Therefore, the influence of radiation and of kinetics on the regression rates can be viewed in the curves of both injectors.

The next analysis should deal with the difference in regression rates results. It is reasonable to assume that the difference is due to the injection methodology, more precisely the velocity profiles.

The swirl injector inserts the oxidizer with basically two velocity components: axial and tangential. The axial flow mixes in a less efficient way than the tangential flow. It is know in the literature that tangential velocities on the grain surface flatten the boundary layer and, therefore, the flame zone (Yuasa *et al.* 1999) and increase the heat transfer (Carmicino and Russo Sorge 2007), which in turn increases the regression rates in comparison to the axial flow. The regression equation for each configuration is shown in Table 3.

The typical exponent of the mass flow mentioned in the literature has values smaller than 0.8, corresponding to correlation with the turbulent boundary layer fully established (Marxman and Gilbert 1963). High values of n imply significant dependence of mean regression with the flow of oxidant. Values of n close to 0.4, which is the theoretically expected value for kinetically controlled regime, mean the combustion is kinetically controlled and less dependent on the oxidizer incoming flux (Pastrone 2012).

The values obtained in the literature for the experimental parameter n from the regression rate equation are listed in Table 4. The experimental parameter n found in this study (0.5 mm/s) is in accordance with the values found in the literature of 0.5; these values are marked in bold.

All tests with axial injector harmed the injector material as shown in Fig. 9, the integration of a long pre-chamber was imperative. The flow downstream the injector exit forms a recirculation zone, which blocks heat transfer from the flame to the bulkhead. Therefore, there is no need for insulation in the swirl case. The same barrier effect was obtained and documented by Jones *et al.* (2009). This is one additional reason to use swirl injector.

Table 3. Regression rate experimental parameters.

Injector	a_0	n	R^2
Axial	0.339	0.259	0.772
Swirl	0.182	0.521	0.636

Table 4. Constant *n* found experimentally for the regression rate equation.

Reference	Injector	Oxidizer/fuel	*n*
Myre *et al.* (2010)	Swirl	$\overline{G}_{OX}$/PE	**0.5**
Carmicino and Russo Sorge (2005a)	Swirl	$\overline{G}_{OX}$/PE	**0.5**
Carmicino and Russo Sorge (2005b)	Axial	$\overline{G}_{OX}$/PE	0.371
Carmicino and Russo Sorge (2005b)	Swirl	$\overline{G}_{OX}$/PE	**0.5**
Knuth *et al.* (2002)	Swirl	$\overline{G}_{OX}$/HTPB	0.54
Yuasa *et al.* (2001)	Swirl	$\overline{G}_{OX}$/PMMA	0.641
Nagata *et al.* (2011)	Swirl	CAMUI	0.8
Present research	Swirl	$\overline{G}_{OX}$/PE	**0.52**
Present research	Axial	$\overline{G}_{OX}$/PE	0.26
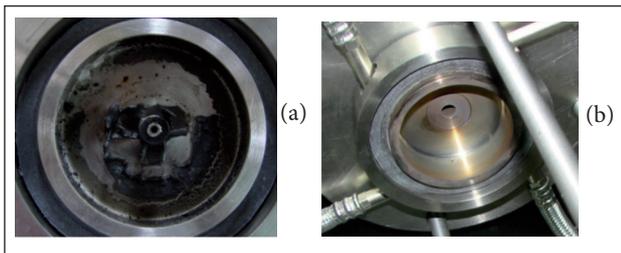
Figure 9. Comparison between injector cross-sections after firings. (a) Axial test; (b) Large swirl test.

than the axial one, which is in accordance with the literature data (Carmicino and Russo Sorge 2005b; Knuth *et al.* 2002; Kumar and Kumar 2013). The experimental parameters of the regression rate equations were compared to the literature. It was found that the results are again in accordance with the literature. The theory of diffusion was applied, and it was possible to correlate the regression rate plot to the three main phenomena: radiation, diffusion and kinetic effects (Marxman and Gilbert 1963).

CONCLUSIONS

The objective of this research was to evaluate and compare the regression rates of polyethylene fuel grains under swirl and axial oxidizer injection methods. Swirl injector yielded better conditions

ACKNOWLEDGMENTS

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