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Experimental Investigation of Showerhead injectors on Performance of a 1-kN Paraffin-Fueled Hybrid Rocket Motor

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Abstract

This paper analyzes the results obtained from a series of static firing tests of a 1-kN lab-scale hybrid rocket motor using four showerhead injectors, namely SH1, SH2, SH3 and SH4, and liquid nitrous oxide and pure paraffin as propellant. The SH1 is delivering 400 g/s oxidizer mass flow rate through 11 holes of 1.4 mm diameter, used as a benchmark. The other three injectors (SH2, SH3 and SH4) have an average oxidizer mass flow rate of 550 g/s configured with 11, 21 and 71 holes of 1.9, 1.4, and 0.8 mm diameter, respectively. The Sauter Mean Diameter (SMD) is decreasing from SH2 to SH4 by reducing the hole diameters. Axial injectors are interesting because of their relatively easy design and the stable signal of the chamber pressure generated during the combustion phase. The tests performed using SH2 and SH3 do not present any noticeable difference on the motor overall performance. The paraffin grains after the tests using SH4 have various small scratches whilst the one using SH2 is much smoother. The increase in smoothness results from the increase in holes diameter. The injector with the smallest orifice diameter (SH4) results in the highest regression rate, around 5% higher than SH2 and SH3 injecting same oxidizer mass and oxidizer mass flow rate. We assume that this is partly due to the increase in turbulence and the reduced droplet size generated with this injector.

1. Introduction

In recent past hybrid rocket motor propulsion systems have received substantial renewed interest as possible design alternatives to presently used liquid and solid propulsion systems. This renewed interest is principally due to the inherent advantages over the other chemical propulsion systems, in particular the safety aspects and capability to control and throttle the motor thrust at low cost. However, this technology has some development lacks in comparison with the other more mature propulsion systems, as liquid and solid rockets. One of the principal drawbacks of the hybrid technology is the low regression rate of the solid fuel, hence the relatively poor combustion efficiency and too low specific impulse [1], [2].

Several regression rate enhancement technics have been tested over the last decades, such as: addition of metal powders to increase the radiative heat flux to the surface of the solid fuel; this leads to higher viscosity and thus makes the manufacturing process more difficult [3]. Multiple ports in the fuel grain to increase the burning surface, but such complex geometry eliminates the desired simplicity [4]. Fundamentally, the limit on regression rate for conventional hybrid fuels is set by the physical phenomena of heat and mass transfer from the relatively remote flame zone to the fuel surface [5].

An interesting promising solution is the use of liquefying fuels, as paraffin. Lab-scale investigations by Karabeyoglu, have shown 3 to 4 times higher regression rate than conventional hybrid fuels. Karabeyoglu has extensively studied the paraffin-based hybrid fuels and developed a liquid layer theory [4], [6]–[8]. The reason for this improved performance because paraffin combustion mechanisms are different from those of traditional fuels

Moreover, the oxidizer injection characteristics play a substantial role in hybrid rocket motor performance [9], [10]. In typical configurations, a liquid oxidizer is injected into the combustion chamber by means of an atomizer and a spray is formed. The liquid oxidizer droplets vaporize in the pre-chamber, flow through the combustion port and react with the fuel grain to achieve stable combustion. Thus, the combustion process will be severally influenced by the incoming oxidizer flow pattern. In fact, the flow characteristics can significantly affect the overall behavior of the motor in terms of thrust, fuel consumption, combustion efficiency and combustion stability [11]. Due to the

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importance of the atomization process on the combustion performances, the injection system design and its different configurations have been mattered of study over the time.
Probably, the most common injector plate is a showerhead (SH) type. The SH injector sprays oxidizer into the combustion chamber through concentric rows of orifices. There is also self-impinging, and non-impinging stream patterns [10], [12]. The showerheads that use parallel injection ports are easy to manufacture. The holes distribution and their dimension determine the spray characteristics.
In this work four different showerhead injectors were designed, manufactured and tested in order to investigate the influence of the injector's configuration on the motor's performance. The study was performed by firing tests using 1kN lab-scale hybrid rocket motor developed at Université Libre de Bruxelles (ULB) in collaboration with Royal Military Academy of Belgium (RMA).

2. Oxidizer injection system design

The four injectors used in this research are tested under the same motor conditions (fixed combustion chamber and post-chamber geometry). All injectors are manufactured in aluminum. The ULB-HRM motor is developed to delivery 1 kN thrust, which is related with the total mass flow rate by the equation (1), where F is the thrust, I_{sp} is the specific impulse and g_o is the standard acceleration of gravity. The total mass flow rate ($\dot{m}$) and the oxidizer mass flow rate ($\dot{m_{ox}}$) are related through equation (2). Equation (3) shows the main variables that influence the oxidizer mass flow rate, as the discharge coefficient (C_d), the number of individual injectors (N_{inj}), the area of the injector (A_{inj}), the oxidizer density (ρ_{ox}) and the pressure drop in the injector (ΔP). The injectors were designed based on the theoretical parameters of the ULB-HRM motor, Table (1), with the goal to delivery 550 *g/s* based in an injector pressure drop of 25 bar.

$$F = \dot{m} \cdot I_{sp} \cdot g_o \quad .(1)$$

$$\dot{m} = \dot{m}_f + \dot{m_{ox}} \quad .(2)$$

$$\dot{m}_{ox} = C_d \cdot N_{inj} \cdot A_{inj} \cdot \sqrt{2 \cdot \rho_{ox} \cdot \Delta P} \quad .(3)$$

Table 1: Theoretical parameters of the ULB-HRM

Parameter		**Parameter**	
Oxidizer	N_2O	O/F shift (theoretical)	~ 7.9
Fuel	Paraffin	Oxidizer mass flow rate (g/sec)	550
Nominal thrust (kN)	1.0	Average Fuel mass flow rate (g/sec)	70
Chamber pressure (bar)	20 to 30	Total mass flow rate (g/sec)	620
Nozzle expansion rate	5.2	Operation time (s)	5 to10

2.1 Benchmark shower head injector (SH1)

The 3D-model of each injector was done using the commercial software SolidWorks® and manufactured at ULB. The SH1 injector is presented in figure (1). It has 11 orifices with 1.4 mm diameter and 7 mm as length, which are spread equally in two different radiuses and one orifice in the center in order to deliver a homogenous distribution of the oxidizer into the combustion chamber.
To initiate the design of the injector, a discharge coefficient should be proposed. for SH1 a value of 0.6 as discharge coefficient was proposed for the design as in Refs. [1], [13]. In order to qualify the design of SH1, a discharge coefficient tests were made using water. Figure (2) brings the comparison between the design and the experimental results of the discharge coefficient (C_d). The results of the discharge coefficient consist of 5 individual measurements that we averaged. We notice clearly that the experimental C_d is lower than suggested value, in tun lower oxidizer mass flow rate

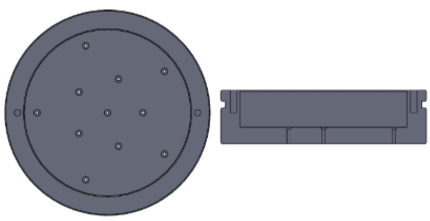

Figure 1: Benchmark shower head injector (SH1)

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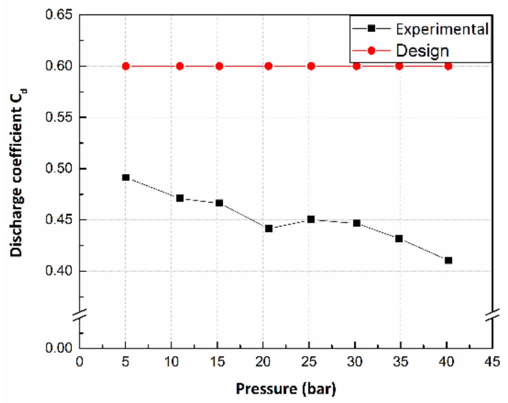


Figure 2: Discharge coefficient as function of the pressure drop

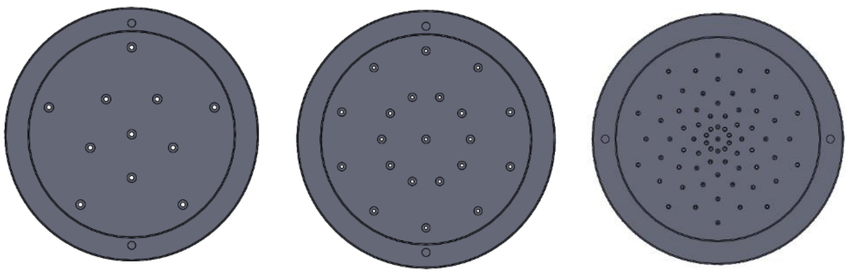
2.2 design of the SH2, SH3, and SH4.

First firing tests were carried out using the benchmark injector. after analysing the data, we found that the reel discharge coefficient using liquid nitrous oxide is 0.32. Based on this value we designed and manufactured three other injectors (SH2, SH3 and SH4) presented in figure (3). The oxidizer mass flow rate is fixed at 550 g/s for all these three injectors to make a fair comparison. The SH2 has the same configuration but the orifices diameter is larger, therefore the mass flow rate is higher. The SH3 and SH4 differ by the number of orifices and their distribution density on the injector's surface. 0Figure (4) presents the Sauter Mean Diameter (SMD) calculated by the equation (5). It increases as the diameter of the injector orifices increases, maintaining the same oxidizer flow rate through the injector plate.

Based on the theory of a plain orifice injector, the axial injection velocity (u_{ox}) is given by equation (4). It gives an axial velocity of 22.8, 24.4, and 20.0 (m/s) for the injectors SH2, SH3, and SH4, respectively. The SMD is the most widely used type of droplet size estimation, which is the average particle size in the atomized region. It is estimated by equation (4) as proposed by Tanasawa and Toyoda [14].

$$u_{ox} = \frac{\dot{m}_{ox}}{\rho_{ox} \cdot A_{inj}} \quad .(4)$$

$$SMD = 47 \frac{D_{inj}}{u_{ox}} \left(\frac{\sigma}{\rho_{ox\_G}} \right)^{0.25} \left[1 + 331 \frac{\mu_L}{\left(\rho_{ox\_L} \cdot \sigma \cdot D_{inj} \right)^{0.5}} \right] \quad .(5)$$



(a) (b) (c)

Figure 3: Showerhead injectors design (a)-SH2, (b)-SH3 and (c)-SH4

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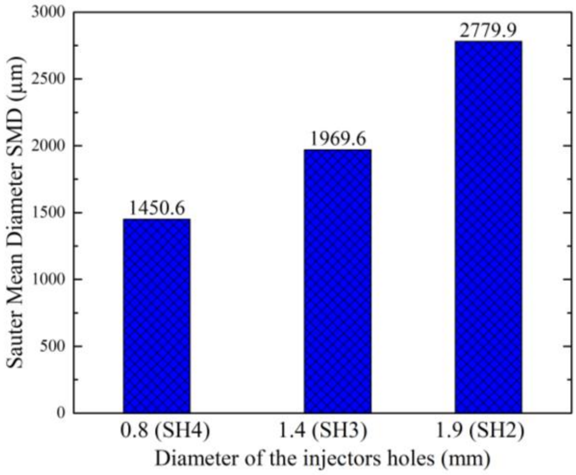

Figure 4: SMD for different orifice diameters of the injector

3. Methodology and governed equations

ULB-HRM test bench is an automatic control system and data acquisition was designed and implemented to conduct experimental investigations on a liquid nitrous oxide/paraffin-based fuel 1-kN hybrid motor, which is described with more details in Ref. [15]. The test stand consists of a horizontal bench that allows quick and secure mounting of the hybrid motor and its subsystems, such as liquid nitrous oxide tanks, feed system, pyrotechnic ignition device, and data acquisition system.
The thrust measured using a load cell and the dimensionless thrust coefficient $C_F$is calculated by equation (6)

$$C_F = \frac{F}{P_c \cdot A_t} \quad .(6)$$

where P_c, is the chamber pressure measured by a piezoelectric pressure sensor. pressure is measured also before and after the injector, and in the test bench tank of the oxidizer. the latter is maintained always at 60 bar. the weight of this tank is tracked by a load cell, to calculate the oxidizer mass flow rate ($\dot{m_{ox}}$) dividing by burning time (t_b).
The fuel consumption is measured by weighing pre- and post-test mass of the solid fuel grain, dividing by t_b we get $\dot{m}_f$. This value with $\dot{m_{ox}}$ used to calculate the average oxidizer-to-fuel ratio $\overline{O/F}$.
The regression rate calculated based on the experimental results is the average value determined by the diameter variation of the fuel combustion port during the total burning time, and is given by equation (7) 7)):

$$\bar{\dot{r}} = \frac{d_f - d_i}{2t_b} \quad .(7)$$

The initial port diameter, d_i, is an input data and is measured before the tests. The final port diameter, d_f, cannot be measured directly due to the complicated (slightly deformed) fuel geometry after combustion. A more precise way to estimate the final port diameter is to use the fuel mass variation expressed by equation (8).

$$d_f = \left[d_i^2 + \frac{4\Delta m_f}{\pi \cdot \rho_f \cdot L_g}\right]^{1/2} \quad .(8)$$

The characteristic velocity c^* is a ballistic parameter that quantifies motor performance and can be used to compare different propellants combinations [1]. The experimental c_{exp}^* is given by equation (9). The combustion efficiency of the motor is expressed by equation (10). It is the ratio of the measured characteristic velocity, calculated by Eq. 9, and theoretical characteristic velocity calculated with the EXPLO5 thermochemical software [16]. The c_{th}^* is calculated for each firing test because different injectors and conditions give a variation in the chamber pressure and the O/F ratio. The data to estimate c_{th}^* is generated with the Explo5 software [16].

$$c_{exp}^* = \frac{\overline{P_c} \cdot A_t}{\overline{\dot{m}}} \quad .(9)$$

$$\xi = \frac{c_{exp}^*}{c_{th}^*} \quad .(10)$$

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In the data analysis, two different combustion efficiencies were specified and calculated, as defined in Ref [12]. First, it is calculated applying Eq. 10, with a c_{th}^* corresponding to $\overline{O/F}$. This efficiency represents a realistic estimation of the motor performance because it uses an experimentally measured average oxidizer-to-fuel ratio. A second combustion efficiency is calculated related to the optimum condition (i.e. using c_{th}^* corresponds to O/F_{opt}) regardless the result of $\overline{O/F}$.
In figure (5) the theoretical characteristic velocity at 17.5 bar combustion chamber pressure is presented. The experimental characteristic velocity is represented by a red rhombus. Two additional points are highlighted in this graph:
"1": the theoretical characteristic velocity corresponding to $\overline{O/F}$.
"2": the theoretical characteristic velocity corresponding to O/F_{opt}.
Thus, the first defined efficiency at $\overline{O/F}$ is obtained using a value of c_{th}^* at number "1", and the second efficiency of optimum O/F is calculated using a value of c_{th}^* at number "2".

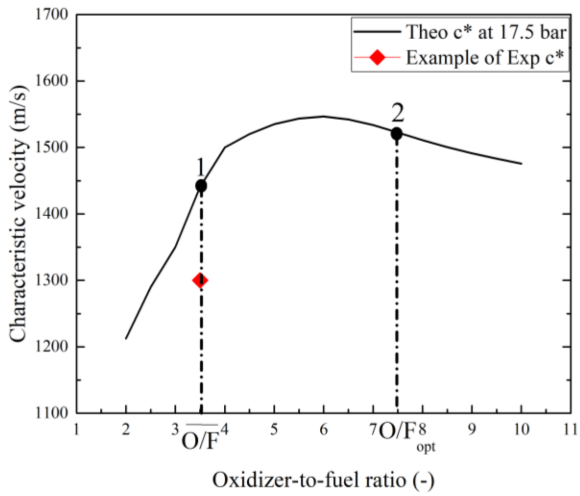

Figure 5: Characteristic velocity graph showing the calculation method of the efficiencies [12].

4. Experimental results

The firing tests were conducted at the 1 Wing Air Base of Belgium at Beauvechain. No major problems occurred during these campaigns, except a few tests where mass of the N2O tank or thrust were not correctly recorded. These ones have not been post-processed.
This work aims to study the influence of the showerhead injector geometry, as number and size of holes, and its impacts on the overall performance of hybrid rocket combustion were investigated

4.1 Mass flow rate and coefficient discharge

One of the first things that had to be investigated was the oxidizer mass flow rate to confirm whether the design target value of 550 g/s was obtained. The importance of this variable lies in the fact that a fairly comparison between the three injectors is possible when similar conditions are achieved. Taking into consideration every performed successful test, average oxidizer mass flow rate $\overline{\dot{m}}_{ox}$ values of 533.5 g/s, 539.7 g/s and 544 g/s were obtained for the injectors SH2, SH3 and SH4, respectively. This signifies that the design was done properly. The real discharge factor was calculated to be 0.32 which is very close to the hypothesis of 0.33 that was based on previous experimental results of the SH1.

Influence of the size and distribution of orifices

For the showerhead injectors many firing tests were performed as presented in Table (2). All initial conditions (injection pressure, initial port of fuel grain, grain length, grain composition) were kept the same.

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Table 2: Test results obtained with SH2, SH3 and SH4 injectors (average values).

Test n°	P_{tbt}, bar	d_i, mm	t_b, s	$\overline{\dot{m}}_{ox}$, g/s	d_f, mm	$\overline{G}_{ox}$, g/cm^2s	$\overline{O/F}$	$\bar{r}$, mm/s	I_{sp}, s	P_c, bar	C_F	ξ, % at O/F_{opt}	ξ, % at $\overline{O/F}$
SH2-1	60.0	30.0	5.29	529.2	105.6	14.7	3.6	7.18	172.2	24.1	1.25	88.8	93.3
SH2-2	60.0	30.0	5.23	542.5	107.4	14.6	3.6	7.28	161.8	24.4	1.18	88.0	92.4
SH2-3	60.0	30.0	5.27	528.9	107.8	14.2	3.4	7.41	161.2	23.1	1.23	84.2	90.3
SH3-1	60.0	30.0	5.29	538.3	105.5	14.9	3.5	7.33	162.0	22.8	1.27	82.1	87.0
SH3-2	60.0	30.0	5.23	543.2	105.5	15.1	3.6	7.22	171.5	23.8	1.29	85.8	89.8
SH3-3	60.0	30.0	5.27	537.6	107.8	14.4	3.5	7.38	174.5	24.4	1.28	88.0	93.3
SH4-4	60.0	30.0	5.08	550.0	108.3	14.6	3.5	7.70	169.0	24.1	1.27	85.3	90.4
SH4-5	60.0	30.0	5.16	537.5	109.4	14.1	3.5	7.69	166.8	23.3	1.28	83.9	89.0
SH4-6	60.0	30.0	5.11	544.5	107.8	14.6	3.5	7.61	165.6	24.3	1.30	87.0	92.3

The influence of injection elements orifice dimensions on the regression is presented in figure (6). SH4 clearly has the highest regression rate for the same average oxidizer mass flux. An increase of 5 % is achieved compared to SH2 and SH3. This implies that for an equal $\overline{G}_{ox}$ the injector with the smallest orifice diameter has the highest regression rate. We assume that this can partly be attributed to the increase in turbulence and the smallest droplets that are generated with the SH4 injector due to its design, and it allows better distribution of the oxidizer while the grain increase the combustion port during operation of the motor. In the configuration as presented in figure (7), initially, for the injector SH4 and the fuel grain with port diameter d_i= Ø30 mm more oxidizer droplets were injected directly in the port compared to SH2 and SH3. Between the SH2 and SH3 injectors, as presented in figure (8), there is no major difference in the performance of the motor. SH4 exhibits an increase of the I_{sp} and C_F meaning that there is more thrust generated for the same amount of regressed fuel.

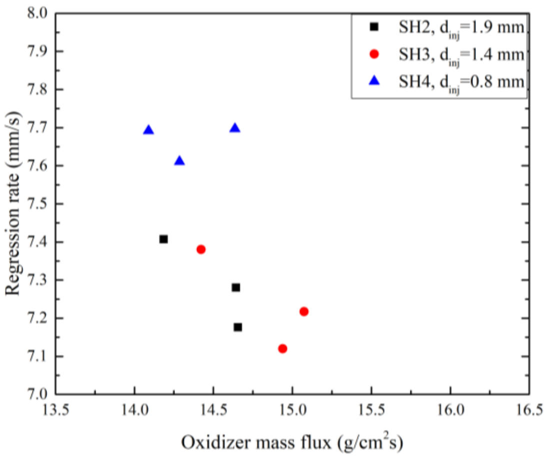
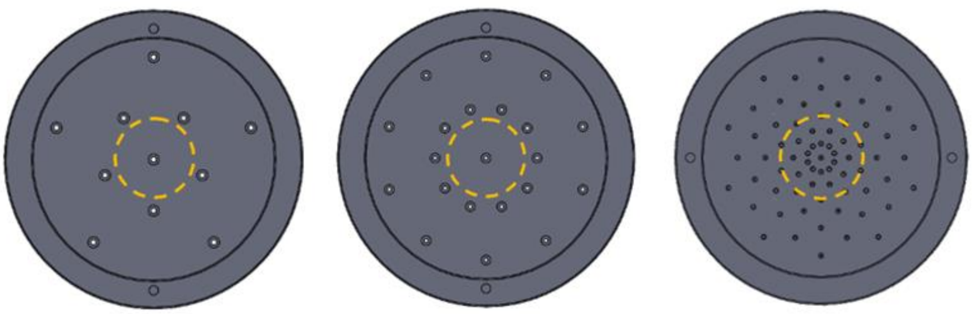


Figure 6: Regression rate in function of the average oxidizer mass flux for the different showerhead injectors



(a) (b) (c)

Figure 7: Representation of injector holes distribution with initial port grain diameter: (a)-SH2, (b)-SH3 and (c)-SH4

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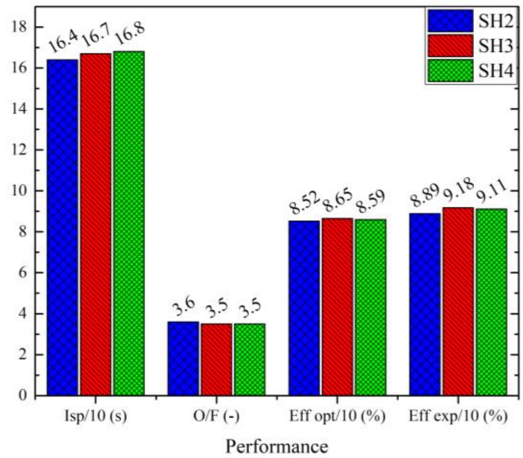

Figure 8: Comparison of the specific impulse, $\overline{O/F}$ and the efficiencies between different SH injectors.

The fuel grains used with SH2 and SH3 injectors after combustion exhibit longitudinal channels and their burning surfaces are smooth (Fig. 9_a & b)). The one with SH3 (Fig. 9_b) has more channels than the grain used with SH2 (0 9_a) because the number of elements in SH3 is increased. The grain tested with SH4 has a lot of craters (small dots) due to the distribution and the number of injector's holes. Seemingly in the latter there is more turbulence generated, which helps to increase the regression rate (see Fig. 6).

(a) (b) (c)

Figure 9: Illustration of the grain interior after combustion for fuel grains with: (a)-SH2, (b)-SH3 and (c)-SH4

4. Conclusions

In this paper, a series of firing tests with different showerhead (SH) injectors configuration is presented. In the first part the quality of the benchmark injector is analyzed, further, the design of the three other showerhead injectors was correctly done. In the second part the work, the effect of the size, distribution, and number of the orifices is studied.
Particularly, this work helps to enrich the technical literature with experimental measurements of N_2O/paraffin firing tests, which are relatively rare in the current open literature. First because hybrid rocket motors are not extensively studied as liquid and solid propulsion systems. Secondly, the study gives a reliable comparison of different showerhead injectors' performance as they have been tested in the same motor configuration. Showerhead is one of the most common type of injector plate which allows the obtained data to be compared with others experimental and theoretical researches.
To study the influence of the injector holes diameter, three injectors were compared: SH2, SH3 and SH4 with injector holes diameters of 1.9 mm, 1.4 mm and 0.8 mm respectively. The injector with the smallest orifice size gives an increase of 5 % on the solid fuel regression rate. Concomitant, both SH2 and SH3 present a similar values of average regression rates, 7.3 mm/s.
The injector SH2 and SH3 with an initial port diameter of 30 mm exhibit longitudinal channels whilst the SH4 has many small craters. The increase in smoothness is coherent with the increase in orifices' diameter. We assume that in the latter there is more turbulence generated, which helps to increase the regression rate.
Based on these results the future work should be conducted in terms of fuel grain inner port diameter. The results in this work helps to choose the best injector, which is the SH4.

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