Control Characteristics of a Gel Propellant Throtteable Rocket Motor

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Abstract

Established in the year 2000 by the German authorities, Bayern-Chemie and national Institutes, the national gel propellant team [Bayern-Chemie, Fraunhofer Institut für Chemische Technologie (ICT) & Deutsches Luft- und Raumfahrtzentrum (DLR)] started to develop the technology needed to build a rocket motor burning gelled propellants. The research and development activities were guided by a suitable principal concept for a gelled propellant rocket motor (GRM).

Based on theoretical considerations (regarding functional aspects) and experimental pre-tests (regarding propellant gelatinization and spraying) a motor system was pre-selected. The identified requirements were proven in December 2009 by two successful demonstration flights [3, 6].

The achieved Know-how on motor level, structured in feeding and injection system, burning chamber and gelled rocket propellant (GRP) has been extended in a systematic and application oriented way so that the goal of an effective control of the thrust by throttling the fuel mass flow rate (FMFR) is now realistic. This paper describes the advances in the development of the FMFR controller of the GRM.

1. Introduction

This article describes recent developments at Bayern Chemie in the selection and testing of a gel rocket motor adequate for military and aerospace applications. Bayern Chemie is a company located near Aschau am Inn, a small town around 60 Km East of Munich, Germany. Its main activity field is propulsion for tactical missiles, which includes rocket motors with liquid, solid and gelled propellants, as well as airbreathing ducted rockets and gas generators. It is a 100% subsidiary of MBDA Germany, which is the German arm of the European company MBDA Missile Systems. A gelled propellant rocket motor (GRM) [1, 2, 3, 4] combines the advantages of a solid rocket motor (SRM) - easy handling and long storage time – with those of a liquid rocket motor (LRM) – thrust modulation / shut-off capability and the potential for long operation times. The reason for this is that the gelled rocket propellant (GRP) is essentially solid in the tank and is liquefied upon injection into the combustion chamber. The GRM performs better than both solid and liquid rockets in terms of:

- Safety – no explosives, no highly flammable liquids
- Insensitivity in case of accidents, because the propellants are no explosives, there is no spillage in case of leakage or perforation of the tanks, and gels have much lower vapour pressure than liquid fuels and hence a significantly lower evaporation rate in case of destruction of the tank. The result is that our gelled rocket propellant (GRP) is hardly flammable under ambient conditions.

Other advantages of GRP are:

- Solid particles can be suspended without the risk of sedimentation during long storage times. This increases the density and particularly the I_{sp} of the propellant, but increases the generation of smoke
- No sloshing of the GRP in the tank when subjected to acceleration or vibration

Shortcomings compared to a SRM are the need for a separate combustion chamber and a tank pressurization system and, compared to LRM with pump feeding systems, a tank design that withstands the internal pressure needed to feed the gelled propellant to the injector and spray it into the combustion chamber. Recent developments at BC, nevertheless, showed good operation at a tank pressure level of 5 MPa and an associated combustion pressure level of 2 - 3 MPa, representing common numbers for storable propellant LRM with pressure feeding systems.

Fig. 1 shows the system concept of a GRM with a solid gas generator (SGG) for tank pressurization. This method has been used for the free-flight demonstrators [5, 3, 6] because of its compact design. The GRP flux to the combustion chamber is controlled by a valve control system. Injectors spray the GRP into the combustion chamber. While [5] demonstrated a hypergolic system based on MMH and IRFNA, BC´s monopropellant system [4] needs an igniter. Pressurization by cold inert high-pressure gas is possible as well and may be a good solution for long operation times, as that method does not heat up the tank structures. A detailed overview on the state of GRM technology at BC is given in [3], an introduction to its potential for space applications is given in [7], and an actual update in [8].

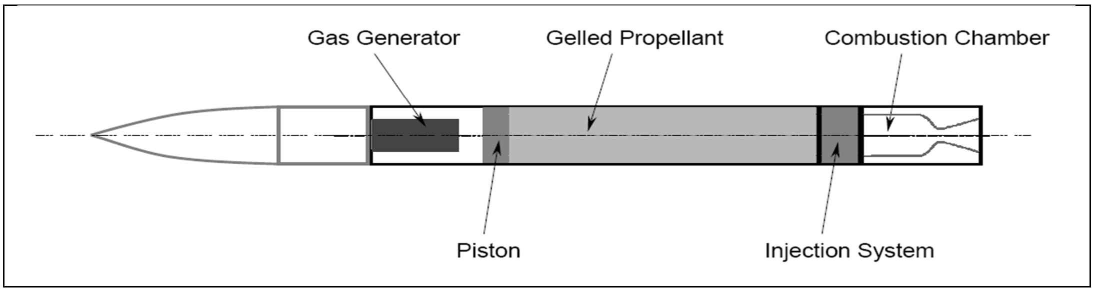

Figure 1: gel propellant rocket motor

2. Characteristics of the GRM at Bayern Chemie

Since 2000, the German National Gelled Propulsion Team of Bayern-Chemie (BC), Fraunhofer Institute for Chemical Technology (ICT), German Aerospace Research Center´s Institute for Space Propulsion (DLR-IRA) and the Bundeswehr Technical Center for Weapons and Ammunition (WTD 91) carries out an extensive study to develop the technology of rocket motors burning gelled propellants. The goal is not only to demonstrate a technical solution, but to create as well the scientific foundation that allows a thorough understanding of the phenomena as the base needed for sustained progress and evolution.

Guidelines of the development are:

- A GRP that is storable for long durations, at least 10 years
- To use ingredients not particularly toxic, carcinogene, acid or in other respects noxious for people or the environment, because the hazard potential of these materials would disqualify them for use in military applications. This disqualified ingredients like hydrazine or its derivates and oxidizers like NTO or IRFNA
- To develop GRP formulations that cover as widely as possible the military operational temperature range from -40 °C up to +71°C. This also excluded aqueous solutions of many oxidizer salts.

The first result of the development activities was a monopropellant throttleable GRM system, burning GRP 001 that was demonstrated by two successful flight tests in December 2009 [3,6]. Since then, the goal of the activities has been to improve the functional and performance parameters of the motor. Key properties of the monopropellant system are:

- Stable start and combustion
- Throttleability
- Wide turn-down range
- A family of monopropellants with different gelling agents, liquid and solid ingredients and additives
- Good scalability of the GRM over the nominal thrust range of 300 to 6000 N at atmospheric pressure, with no indication about a limit to further up-scaling
- Environmental friendliness of propellant and exhaust gas
- Little primary and secondary smoke if no solid additives are used
- Good handling, transport and storage properties
- Long storage time, like solid propellants. An environmental test program similar to that for a SRM, covering 5 years of lifetime was carried out for a GRM with GRP001 and after this program the GRM showed no degradation at a static firing test
- High degree of insensitivity. Tests with GRP001 carried out at the Federal Institute for materials Research and Testing (BAM) yielded the rating “no explosive”. IM-tests carried out at WTD 91 showed mild burning under fuel fire, slow heating and bullet attack and no reaction under fragment attack. Only a shaped charge attack provoked a detonation reaction. A more detailed assessment of the hazard potential of different propellant systems is given in [3]
- A demonstrated operational temperature range from -30 °C to +71 °C. Activities to extend the lower

temperature limit to -40 °C are ongoing.
- Ignition by solid propellant igniters and an external gas lancet has been demonstrated
- Monoblock solid gas generator designs for tank pressurization that allow to cover within a given time frame various thrust profiles, and a method to predict the tank pressure histories dependent on thrust course and GG design which can be used to optimize the ballistic behaviour of the GG
- Comparatively low cost, compared to solid propellant or storable propellants like hydrazine

A penalty to be paid for the high degree of insensitivity is that the GRM needs a comparatively powerful ignition system, which complicates the design of a GRM with repeatable ignition. Hypergolic systems and non-hypergolic bi-propellant systems are a topic of basic research, but not yet sufficiently mature to build a rocket motor.

Table 1 gives an overview on specific impulse I_{sp}, density ρ and combustion temperature T_c of the different propellants of BC's GRP family. Looking for ballistic performance, the maximum I_{sp} of GRP002, GRP004 and GRP013 (for example) is comparable to that of moderately aluminized solid propellants with HTPB as binder and APC as oxidizer. Other propellants like GRP007, GRP008 or GRP010 have a low combustion temperature and are suited for the use in gas generators (GG) that pressurize volumina, e.g. tanks, produce the driving gas for mechanical assemblies or for direction and attitude control systems (DACS). By blending of different ingredients the combustion temperature of the gelled propellant can be adapted to the thermal sustainability of the mechanical structures, e. g. valves or other gas flow control or energy conversion systems that are subjected to the combustion products. Notice that the density of the GRP tends to be higher than that of liquid propellants which are currently in use. Depending on the ingredients to be used for the GRP blend, the cost for the production of GRP is lower than that of other current storable or solid propellants. In addition we can expect that the cost for handling, transport and storage, driven mostly by safety measures, and for disposal, driven by environmental protection methods, are lower.

Table 1: Key parameters of the GRP family

Gel	I_{sp} [Ns/Kg] $p_c / p_\infty = 70:1$	ρ [g/cm^3]	T_c [K]
GRP 001	2248	1.13	2199
GRP 002	2487	1.31	2795
GRP 003	2236	1.18	2089
GRP 004	2586	1.28	2910
GRP 005	2080	NA	1883
GRP 006	2182	NA	1981
GRP 007	1900	1.11	1396
GRP 008	1878	NA	1375
GRP 009	2143	1.19	1904
GRP 010	1749	1.33	1213
GRP 013	2478	1.41	2908

3. Gel Rocket Motor

A test gel rocket motor was assembled at BC in order to verify the control properties of the different GRM. A schematic of the prototype can be seen in Figure 2. Pressurized air forces the injection of the gel stored in the gel chamber through a cylinder with Area A_{gel} and linear movement and velocity given by $x_{gel}, \dot{x}_{gel}$. The mass flow of the gel is regulated with a control valve. Both on-off and proportional control valve types have been considered and tested. The Gel is atomized into fine particles via a set off injector heads into the combustion chamber. All the parameters explicit in the scheme are directly measured and stored during the trial.

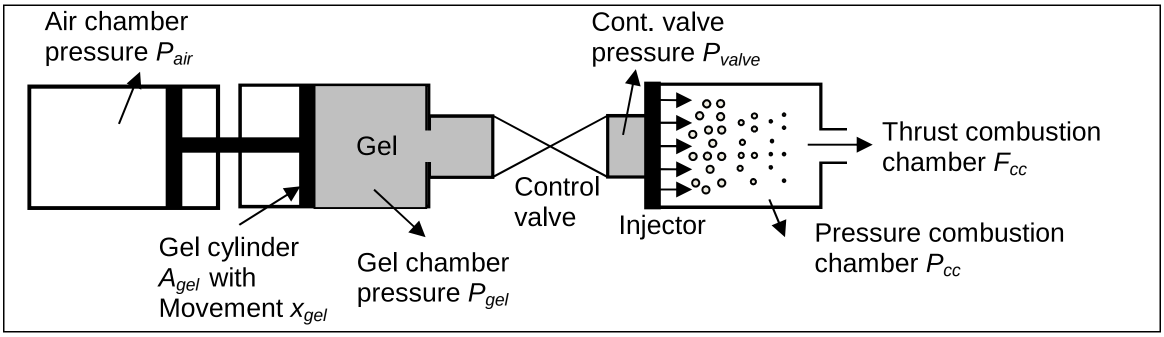

Figure 2: Prototype GRM at BC

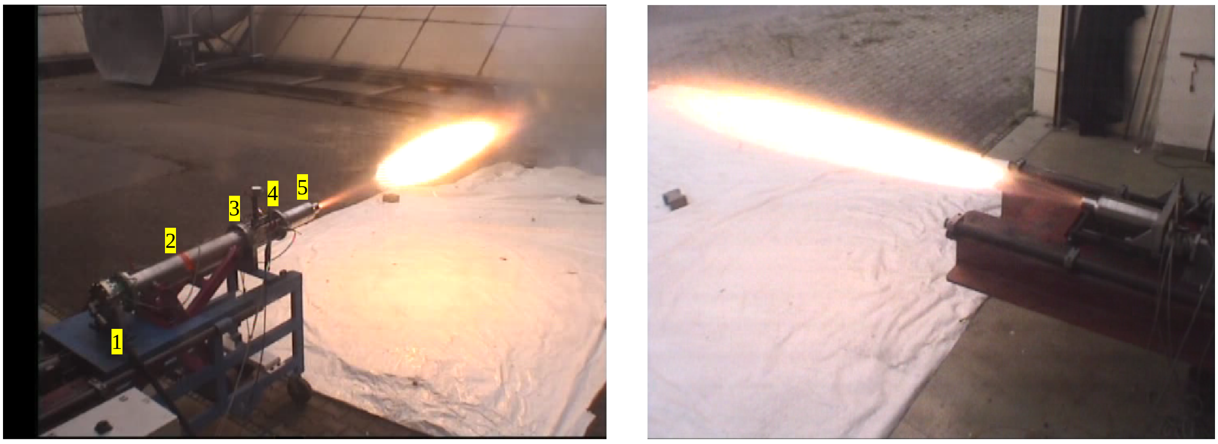

Figure 3: trial photos

Figures 3a and 3b show two different live GRM trials at BC. In Figure 3a it can be seen the 1) air chamber or compressor, 2) gel chamber or tank, 3) control valve, 4) injector head, 5) combustion chamber. Figure 3b shows the trial from a different angle and with a different GRM configuration.

4. Trial description and results

Gel selection trials

A series of trials were performed in order to determine the GRP with the best control characteristics and performance. A brief description of three of those trials is shown in Table 2. The “valid normalised FMFR” column is the interval in which a monotonous control curve can be realized (the larger the better). The “valid normalised Pressure/Thrust” is the combustion chamber pressure and thrust range for the gel in the valid FMFR interval, and the last table on the right shows the linearization error for each curve, in terms of average error and standard deviation. The pressure in the air chamber was set at 200 bar for the three trials, as seen in Fig 4a. The pressure drop from 0s to 1s is due to the characteristics of the testbench air compression system and is not related or has no influence on the motor operation. The gel mass flow $\dot{m}_{gel}$ or FMFR (fuel mass flow rate) can then be computed from the movement (shown in figure 4b) and speed of the control valve by:

$$\dot{m}_{gel} = \frac{dx_{gel}}{dt} \cdot A_{gel} \cdot \rho_{gel}$$

Table 2: Trial results

Trial	**Gel reference**	**Valid normalized FMFR**	**Valid normalized Pressure/Thrust**	**Error in valid FMFR regime** $\bar{e}$ (σ)
A	GRP-001	0.8 - 1	0.7 - 1	0.0113 (0.0068)
B	GRP-002	0.44 – 0.92	0.42 – 0.95	0.0137 (0.0100)
C	GRP-006	0.48 - 92	0.48 – 0.96	0.0131 (0.0093)

The gel density, ρ_{gel} , is given in Table 1. The values marked N/A in the table are not free for publication. The FMFR is shown in Figure 5. The end position of the gel cylinder is not the same for all trials as the system is turned off as soon as flameout occurs, in order to avoid potential damage in the motor and pollution. The different velocities of the gel cylinder are explained by the different rheological properties of each gel.

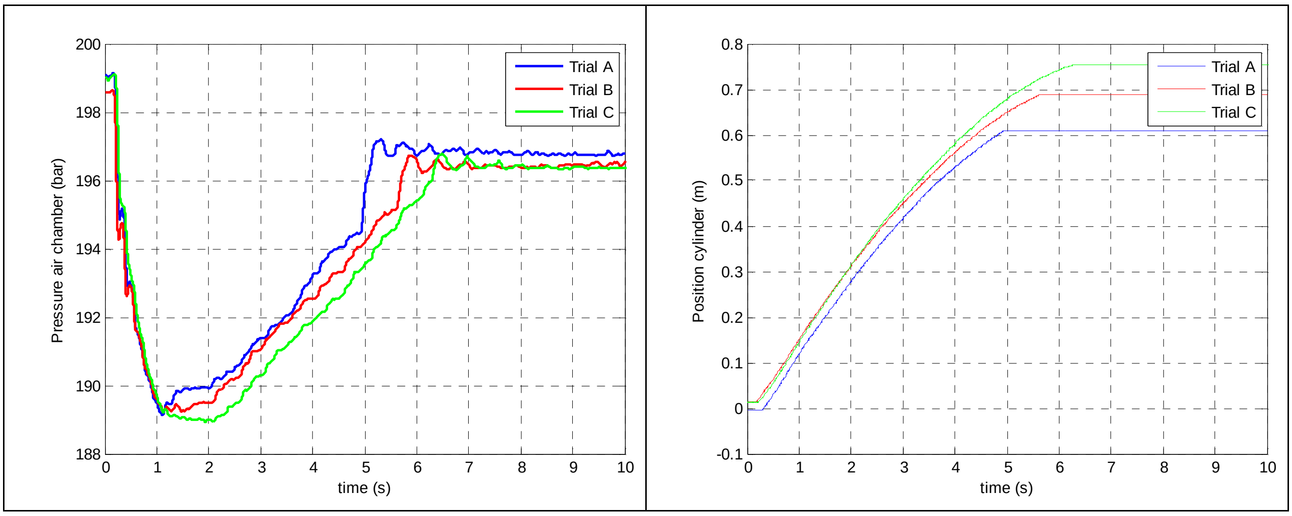

Figure 4a, 4b: Air chamber pressure (a), Gel cylinder position (b)

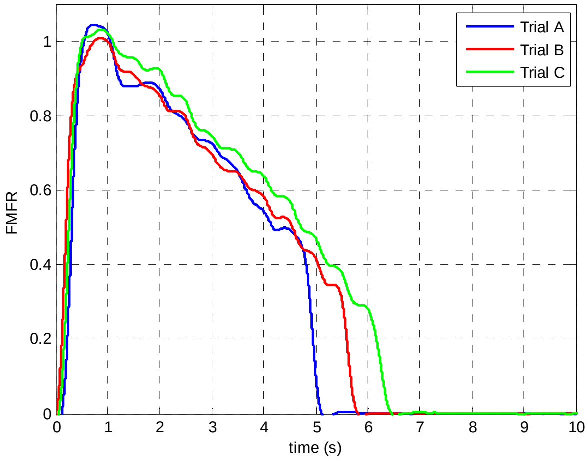

Figure 5: Gel fuel mass flow rate (FMFR)

Figure 6 shows a comparison between the three trials in terms of FMFR and achieved combustion chamber pressure. For control purposes, it is essential to have a monotonic relationship between those two parameters for as large an interval as possible. It can be clearly seen that GRP-001 presents poor control characteristics with little benefits in term of added thrust compared to GRP-002 and GRP-006 (Figure 6b). Its burning quality is poor at combustion chamber pressure lower than 6 MPa as it does not burn completely in the combustion chamber at low pressure conditions. Therefore, the choice is between GRP-002 and GRP-006, as a stable combustion is achieved with both for a wide pressure range. The small oscillations present in the graph in the stable regime come from the commanded valve steps, as a discrete control valve system was used to conduct the trials. This is an indication of the very fast response of the combustion chamber pressure on valve action.

The FRMR – Pressure response of GRP–002 has a slightly higher average error, and standard deviation error, than GRP–006, as it can be concluded from Figure 6c and from the last column of Table 2. All the trials reported here were performed at room temperature. The thrust achieved in the three trials can be seen in Figure 7.

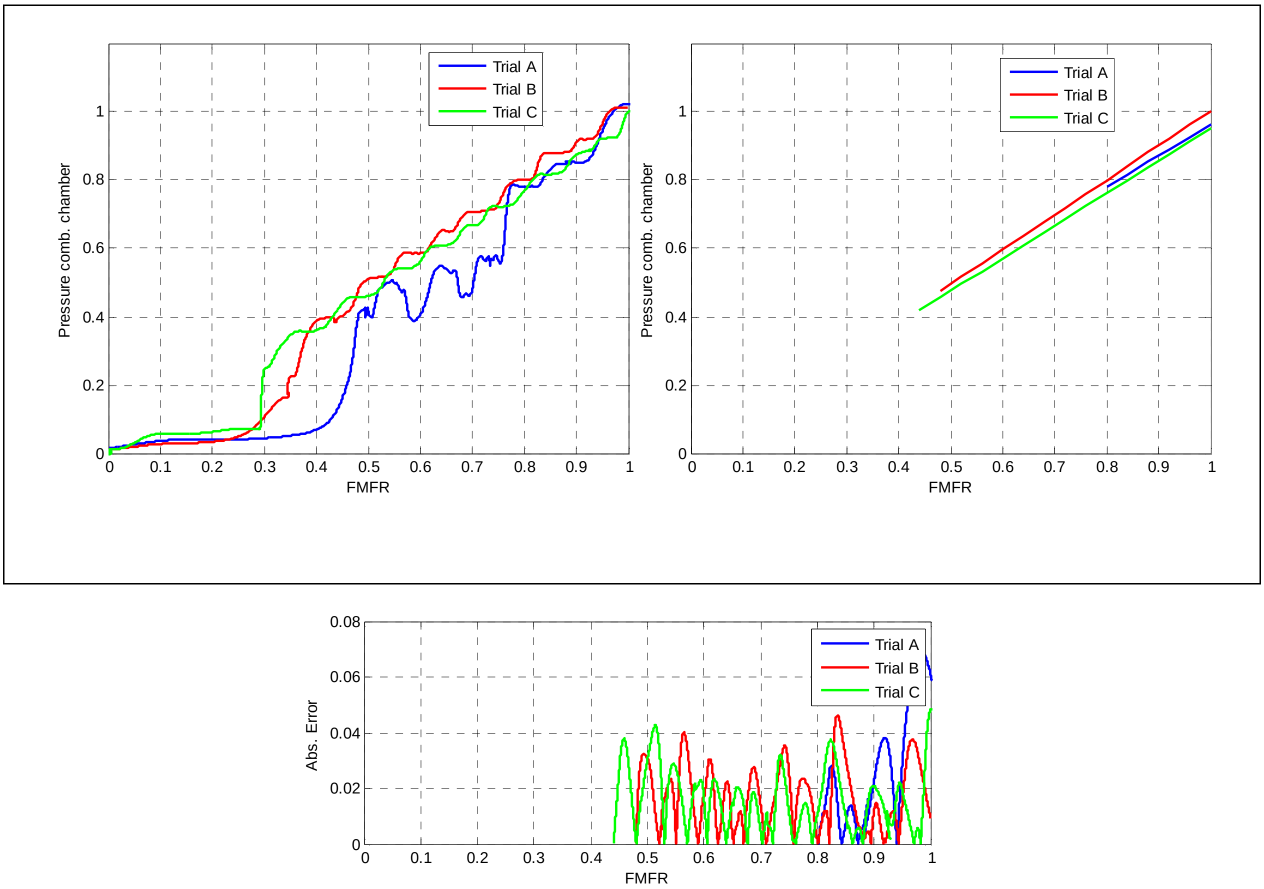

Figure 6a, 6b, 6c: FMFR – Pressure comb. chamber (a), FMFR - Pressure comb. chamber linearized (b), linearization error (c)

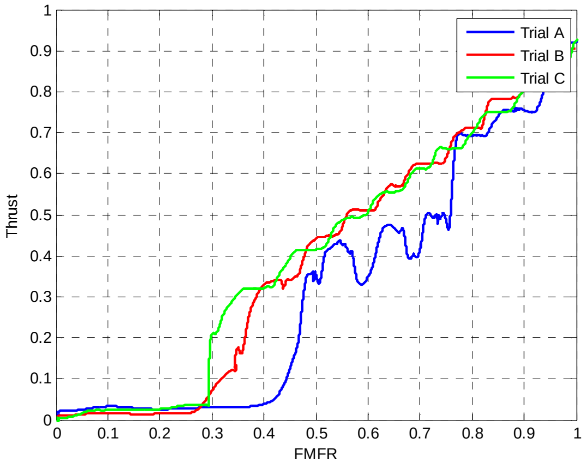

Figure 7: FMFR – thrust comb. chamber

Control trials

Based on results of the gel selection trials, a GRM with GRP-006 was chosen to perform a set of control trials. A series of steps of increasing amplitude were commanded to the gel control valve in an open pressure control loop. Enough time was given between steps for the pressure to settle. The trial comprised of four positive and four negative steps for a total time duration of around 4.7 s. Figure 8a shows the pressure in the air chamber. It was set to 200 bar as for the gel selection trials. The variations during the trial come from the properties of the test bench air compressor system. Figure 8b shows the gel cylinder position from which the FMFR is computed. The gel tank was around 90% full at the beginning of the trial and the trial lasted until burnout, which occurs when the pressure in the combustion chamber drops below the minimum sustainable pressure. The line in Figure 8b is a composition of linear functions with different slopes, the smaller corresponding to the low FMFR step and the larger corresponding to the high FMFR step as seen in Figure 9. The high FMFR step level is kept constant, and the low level FMFR decreases for each step in order to evaluate the response of the GRM for step requests of increasing size.

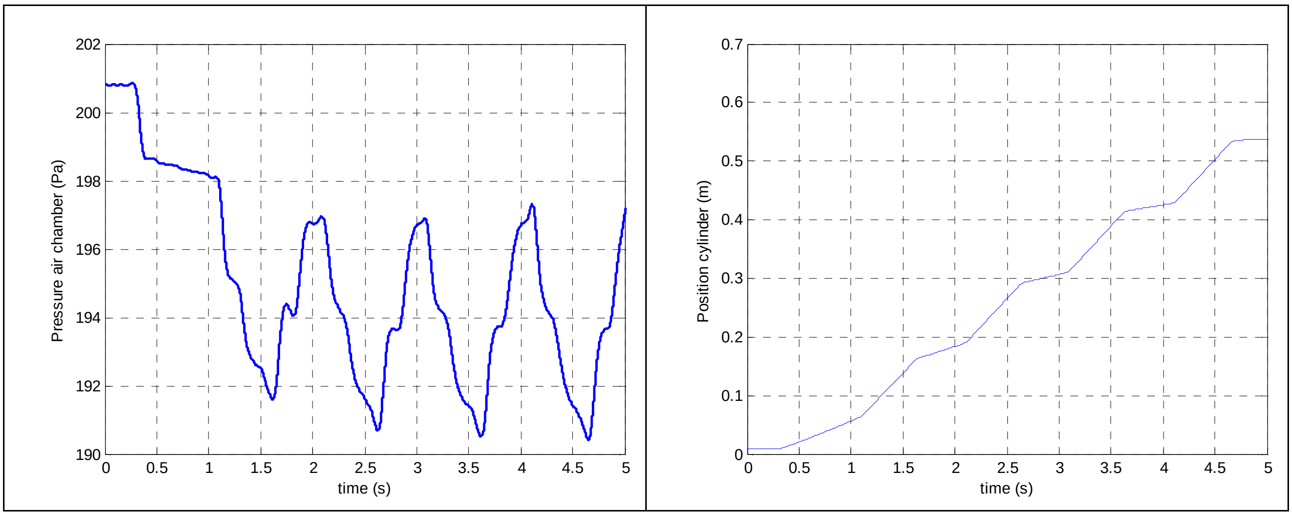

Figure 8a, 8b: Air chamber pressure (a), Gel cylinder position (b) for the control trial

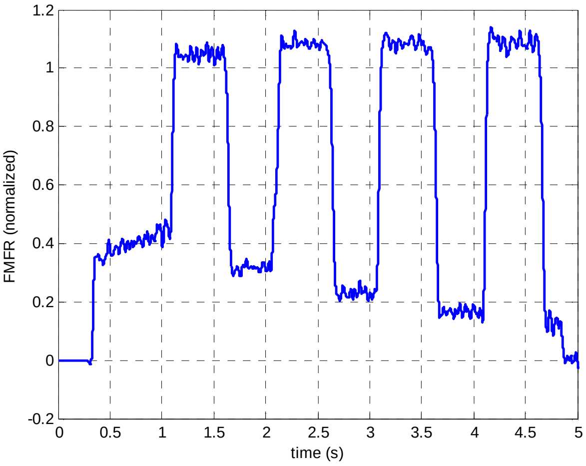

Figure 9: FMFR for step trial (normalized)

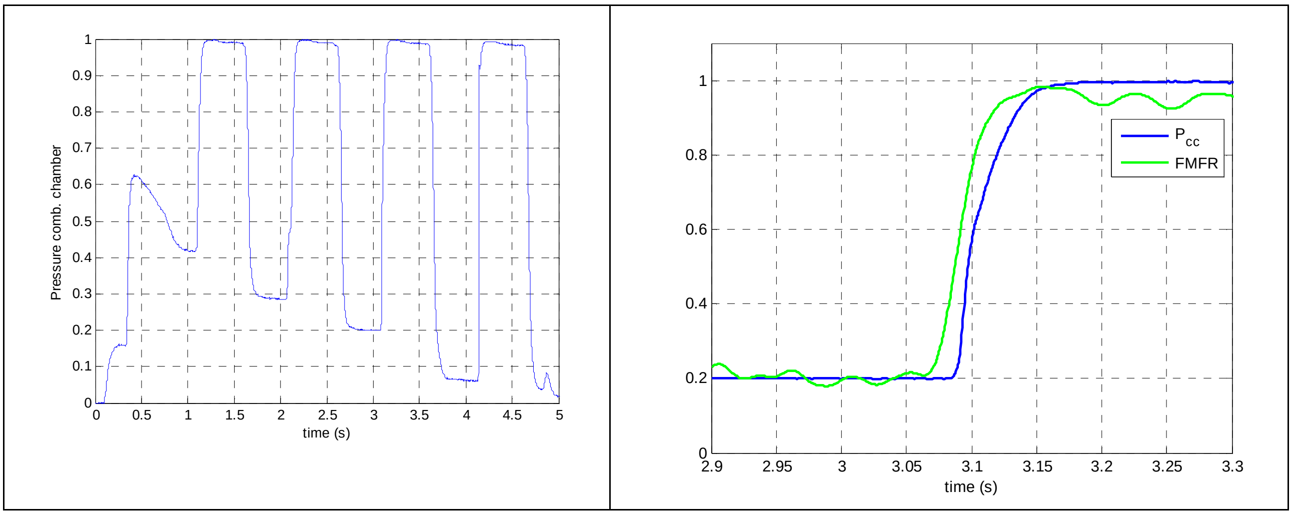

Figure 10a, 10b: Pressure combustion chamber (a), Pressure combustion chamber, FMFR and valve command for step Nr. 3 (b)

Figure 10a shows the normalized pressure in the combustion chamber. The pressure pique at t = 0.4s corresponds to the ignition of the gel in the combustion chamber. Figure 5b shows the step at t = 3.08s in detail. The time delay between a FMFR increase and pressure increase in the combustion chamber is consistently lower than 5 ms.

5. Conclusion

A GRM with the following specific properties:

- Very good storage, transport and handling properties
- Very low hazard potential
- High degree of environmentally friendliness, no corrosivity and very low toxicity
- Lower operational temperature limit of -30 °C
- Operational thrust regime between 300 and 6000 N
-

has been chosen from a group of candidates and its viability for a controlled motor combustion checked. The pressure and FMFR are normalized in respect to maximum reference values which fit the GRM requirements. The trial results, shown in Figure 3, indicate that the motor performs within the desired parameters, with a response time predominantly determined by the response time of the test control valve (i.e. the FMFR).

6. Symbols

F_n	N	Nominal thrust
$I_{sp,vol}$	Ns/dm^3	Volumetric specific impulse
I_{sp}	Ns/Kg	Mass specific impulse
p_{cc}	Pa	Combustion chamber pressure
p_T	Pa	Tank pressure
p_∞	Pa	Ambient pressure
T_c	K	Combustion temperature
t_{op}	s	Time of operation
ρ	Kg/ m^3	Density
A_{gel}	m^2	Area gel cylinder
x_{gel}	m	Linear movement of gel cylinder
$\dot{x}_{gel}$	m/s	Linear velocity of gel cylinder

7. Abbreviations

C/SiC	Carbon fibre reinforced silicium carbide
CFRR	Carbon fibre reinforced resin
DACS	Diver and attitude control system

GG	Gas generator
GP	Gelled propellant
GRM	Gelled propellant rocket motor
HTPB	Hydroxyle terminated polybutadiene
IRFNA	Inhibited red fuming nitric acid
LRM	Liquid propellant rocket motor
MMH	Mono methyle hydrazine
NTO	Dinitro tetroxide
RM	Rocket motor
SGG	Solid propellant gas geneator
SRM	Solid propellant rocket motor
FMFR	Fuel Mass Flow Rate

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