DOI: 10.13009/EUCASS2017-158

Scalability of Gelled Propellant Rocket Motors

P. Caldas Pinto, N. Hopfe, J. Ramsel, W. Naumann, A. Thumann, G. Kurth
**Bayern Chemie GmbH*
D-84454, P.O. Box 1131, Aschau am Inn, Germany

Abstract

Work on gel propulsion began in Germany in 1999. The German Gel Propulsion Technology Program started in 2001 from a white sheet of paper, proposed by the DLR Institute of Space Propulsion, Bayern-Chemie and the Fraunhofer Institute of Chemical Technology. Aim of the first phase was to develop the technology needed to build a rocket motor burning gelled propellants and to demonstrate its operability by a free flight within significantly less than a decade. The research and development activities were guided by a suitable principal concept for a gelled propellant rocket motor Based on theoretical considerations (regarding functional aspects) and experimental pre-tests (propellant development, gelation, rheology, spraying, ignition and combustion) a motor concept was pre-selected and the motor developed. The identified requirements were proven in December 2009 by two successful demonstration flights [1,2]. Two static trial campaigns have taken place between 2010 and 2014 with the objective to improve the performance of the GRM and to optimize and demonstrate the control performance of the GRM.

This paper analyses the scalability of the Gelled Rocket Motor (GRM) technology, based on theoretical scenarios simulated at Bayern-Chemie, and on the expertise accumulated since the demonstration flights. After a brief introduction to the topic, three different concepts will be analysed: The applicability of GRM for conventional missiles, for ACS/DACS exo-atmospheric systems and for micro-motors.

1. Introduction

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 solid and gelled propellants, as well as airbreathing ducted rockets. It is a 100% subsidiary of MBDA Germany, which is the German arm of the European company MBDA Missile Systems. This paper focuses on the scalability of the Throttleable Gelled Rocket Motor (GRM) as designed and tested by Bayern-Chemie as the propulsion system for future missiles [3,4], sounding rockets [5] and divert and altitude control systems (DACS) [6].

This article is divided in 6 sections. Section 2 concerns the current state of the gel propellant development at Bayern Chemie. In section 3, a description is given of the green GRM characteristics and performance is given. This is followed by an overview of trials performed with multiple motors are Bayern Chemie is given, in order to demonstrate the scalability of the GRM technology, as well as its application. Finally, an overall summary of the article is given in section 6.

2. Gel Rocket Propellant Technology

In the last two decades a growing interest in gelled propellants, propellants or propellant combinations for rocket and ramjet propulsion applications can be observed worldwide. Gelled propellants have the potential to combine major positive properties of liquid and solid propulsion systems without combining major disadvantages. This means in detail that a gel rocket motor combines thrust variation on demand, i.e. an advantageous characteristic of liquid rocket motors, with the easy handling and storage characteristics of solid rocket motors. Also for air-breathing ramjets the use of gel propellants is advantageous because of better safety aspects in comparison to liquid propellants [7,8].
The possibility to combine these above mentioned properties is caused by the non-Newtonian rheological behaviour of gels. Gels are solid at rest and are thus easy to handle and store, similar to solid propellants. Under a sufficiently high applied shear stress, however, they can be liquefied whereas their viscosity decreases with increasing applied shear stress.
The origin for the development of a gel rocket motor (GRM) was the demand to realize a rocket motor with variable thrust, easy handling and storage characteristics and lower hazard potential than typical solid and liquid rocket motors (LRM). The requirement of environmental friendliness on propellants and exhaust, commonly

DOI: 10.13009/EUCASS2017-158

designated as "green propulsion", was also added. For the German Gel Propulsion Technology Program (GGPT) [4], the absence of toxic and thus hazardous ingredients like hydrazine and its derivatives, N2O4 (NTO) and HNO3 (IRFNA) was an initial key requirement. The requirement of long-time storability of the propellants excluded ingredients that exhibit autocatalytic processes, are otherwise chemical unstable or are not storable under ambient temperature and pressure like N2O or cryogenic liquids.

A GRM or Gel Gas Generator (GGG) shares with the liquid rocket motor (LRM) the separation of tank and combustion chamber and with solid rocket motors (SRM) the essentially solid nature of the propellant as long as it rests in the tank. The essentially solid state of the propellant in the tank reduces the hazard potential significantly because in case of damage or an accident the gelled propellant:

- Does not spill
- Produces no large evaporation surface
- Has a much lower vapour pressure than the liquid
- Does not soak into the ground

Like for LRM, thrust control is possible by control of the gelled propellant mass flow rate. The key ingredients of an effective GRP are a balanced blend of energetic fluids mixed with small amounts of efficient gelling agents. Additives can be used to modify the combustion behavior or other properties of the GRP. If tolerable, solid particles can be suspended in the gel to increase the I_{spec} and / or the density of the GRP, because the nature of the GRP prevents sedimentation or buoyancy of incorporated particles even over long storage times. GRMs can be either bi-propellant or monopropellant systems.

The GRP is fed to the combustion chamber (CC) by a pressure feeding system because a gel cannot be pumped e.g. via turbopumps as in typical larger liquid rocket engines. For smaller liquid propulsion systems, however, pressure feeding systems are equally used. In most cases this is driven by pressurization gases, either produced by a gas generator (GG) or from a high pressure gas reservoir. For a gel rocket motor (GRM) it is advantageous that a piston within a long cylindrical tank or a membrane within a short or spherical tank separate the GRP from the pressurizing gas. The GRP is injected into a combustion chamber in such a way that a spray of small droplets is formed. The very high shear rates produced during the injection process destroy the gel structure and the GRP behaves similar to a liquid propellant (LP).

The thrust level of the GRM can be either controlled by control of the GRP mass flow or by intermittent operation, and a GRM can be shut off on demand at any time

The "solid" nature of GRP also prevents sloshing in the tank, if the tank is subjected to variable acceleration or vibration. Figure 1 shows a sketch of the principle of operation of a GRM.

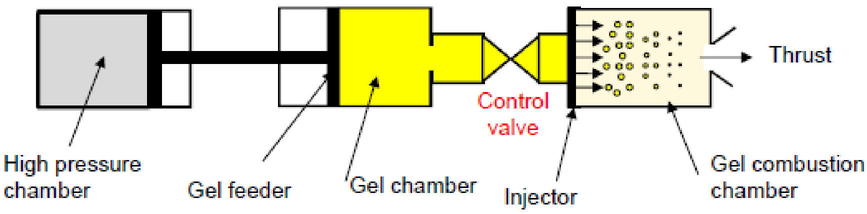

Figure 1: Principle of operation of a GRM

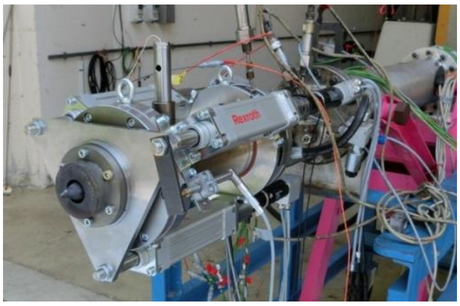


Figure 2 and Figure 3: The highly variable combustion chamber on BC´s static test facility; BC´s GRM demonstrator missile just after launch

DOI: 10.13009/EUCASS2017-158

3. Green GRM Characteristics and Performance

The propellant development guidelines of the German Gel Propulsion Technology program are:

- A GRP that is storable at least 10 years.
- To use ingredients not particularly toxic, carcinogen, acid or in other respects harmful for people or the environment, because the hazard potential of these materials would disqualify them for use in military applications. This disqualifies ingredients like hydrazine or its derivatives and oxidizers like dinitrogen tetroxide or nitric acid
- To develop GRP formulations that cover as widely as possible also the military relevant 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 the two successful flight tests [2]. 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
- 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. An environmental test program similar to that for a solid propellant rocket motor, covering 5 years of lifetime was carried out for a GRM with GRP-001 and after this program the GRM showed no degradation at a static firing test
- High degree of insensitivity. Tests with GRP-001 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 propellant fire, slow heating and bullet attack and no reaction under fragment attack. A more detailed assessment of the hazard potential of different propellant systems is given in [9]
- A wide operational temperature range
- 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 gas generator (GG) design which can be used to optimize the ballistic behavior of the GG

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 actual basic research activities, but not yet sufficiently mature to build a rocket motor.

Table 1 gives an overview on theoretical specific impulse I_{spec}, density ρ and theoretical combustion temperature T_c of the different propellants of BC’s GRP family. The theoretical performance of the propellants has been validated by a campaign of performance test runs. Looking for ballistic performance, the maximum I_{spec} of GRP-002, GRP-004 and GRP-013 (for example) is comparable to that of classic moderately aluminized propellants with HTPB as binder and ammonium perchlorate as oxidizer. Other propellants like GRP-007, GRP-008, GRP-010 or GRP-019 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 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.

DOI: 10.13009/EUCASS2017-158

Table 1: Key parameters of the GRP family

Gel	I_{spec} [Ns/kg] $p_c / p_\infty = 70:1$	T_c [K]	ρ [g/cm^3]
001	2194	2144	1.13
002	2512	2795	1.31
003	2236	2089	1.18
004	2586	2910	1.28
005	2080	1883	1.17
006	2182	1981	1.16
007	1900	1396	1.11
008	1878	1375	1.09
009	2143	1904	1.19
013	2290	2536	1.41
014	2178	1857	1,14
015	2467	2770	1.38
016	2465	2809	1.38
017	2423	2650	1.38
018	2135	2574	1.42
019	1990	1438	1,11
026	2622	3150	1.49
039	2629	3180	1.55

4. Scalability of GRMs

The scalability and controllability of GRM's has been shown at BC through a series of test campaigns at low, medium and high thrust levels. Achieving controlled low thrust levels has a direct application in systems that require micro-adjustments to the trajectory over time. High thrust levels are necessary in order to enable the usage of the GRP in application such as DACS and sounding rockets. A summary of the GRM's developed at BC can be found in Table 2. The trials described in this section show the scalability of the GRM technology and its applicability to different systems.

Table 2: selected GRM Motors at Bayern Chemie

Motor	Description
0-300 N	Injector head with one or two injector elements Used for: fast characterization of new GRPs Component testing Applications that require low thrust and long burning time
0.5-6NkN	Injector head with 15-20 injector elements Missile demonstrator has flown two perfect trial flights
20 kN	Injector head with 60 or more injector elements

DOI: 10.13009/EUCASS2017-158

4.1 Micro-Motor

The GRP micro-motor is used for the fast prototyping of new GRP mixtures, as well as economically testing different components of the motor. It also has direct applicability to systems with low-thrust and long duration firings requirements.

Trial GRM-001

Trial GRM-001 can be seen in Figure 4 in terms of thrust (Figure 4a) and propellant mass flow rate (Figure 4b). The nominal test combustion chamber pressure was 80 bar. The trial duration was set to 60s, in order to test specific materials of the motor for the total operational time of the system. The propellant mass flow rate (PMFR) varied from 0.15 to 0.17 kg/s during the trial.

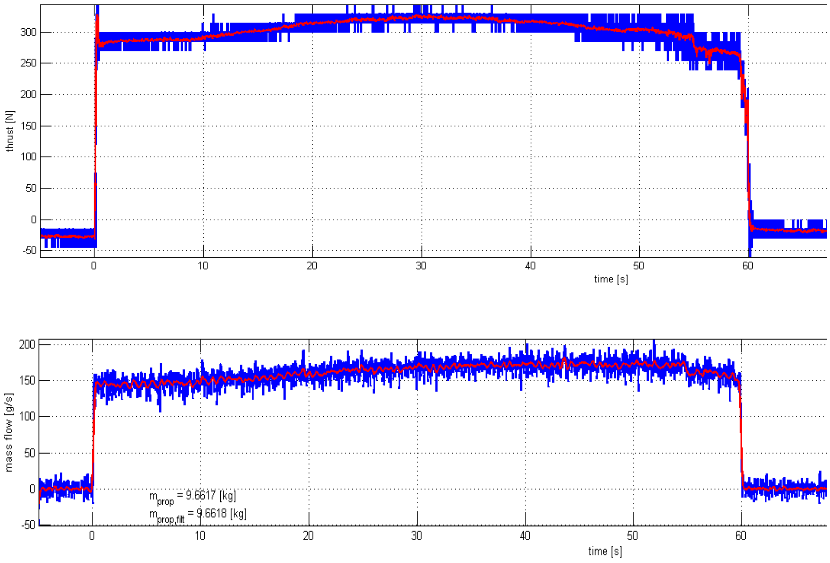

Figure 4a-b: GRM-001 (300 N GRM) thrust and PMFR

4.2 6 kN Motor (Conventional missile)

A principal sketch of a GRM missile is given in Figure 5, which shows a GRM with a solid gas generator for tank pressurization. A detailed overview on the conventional GRM missile configuration is is given in [1,2].

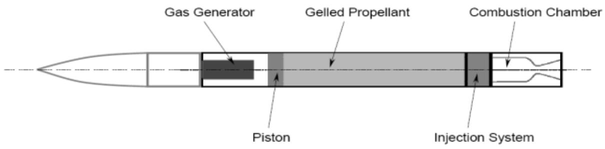

Figure 5: gel propellant rocket motor for a conventional missile

Trial GRM-002

The chosen GRP for GRM-002 was GRP-006 (see Table 1). GRM-01 consisted on a series of step commands with the maximum propellant mass flow rate (PMFR) and thrust level corresponding to the fully open position of the control valve. Enough time was given between steps for the pressure to settle. The trial comprised of four positive and four negative steps for total time duration of around 4.7s. The high thrust step level is kept constant, and the low level thrust decreases for each step in order to evaluate the response of the GRM for step requests of increasing size.

DOI: 10.13009/EUCASS2017-158

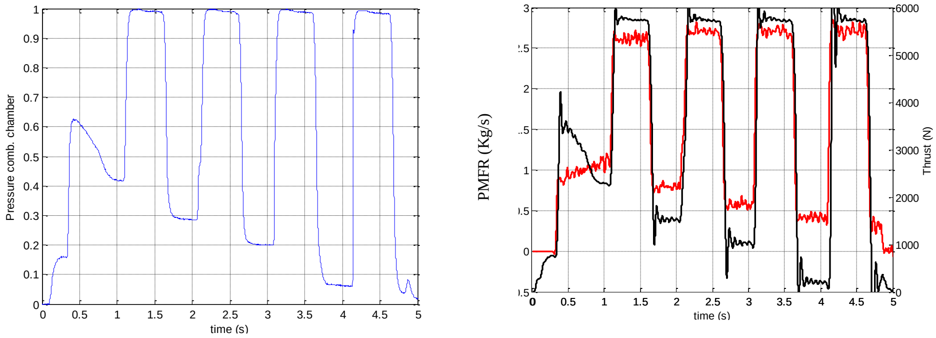

Figure 6a-b: GRM-02 Combustion chamber pressure (a), PMFR and Thrust (b)

Figure 6a shows the normalized pressure in the combustion chamber. Since the pressure control valve was not active, the pressure in the combustion chamber is directly proportional to the amount of propellant being injected. The pressure shown has been normalized. The pressure peak at t = 0.4s corresponds to the ignition of the gel in the combustion chamber. Figure 6b shows the PMFR and thrust. The time delay between a PMFR increase and thrust increase in the combustion chamber is consistently lower than 5ms. The maximum thrust for this GRP and nozzle configuration is 5800 N at around 2.5 kg/s PMFR.

Trial GRM-003

GRM-003 consisted of a pressure controlled long duration trial (t = 85s), with a series of decreasing and increasing step commands during the first 32s of the trial and a constant pressure command from 33 s until the end. The trial end was dictated by the amount of propellant in the tank, as the temperature measurements at the critical structural points (injector head, combustion chamber) were at 80 s well below the tolerance values. Notice that the pressure curve shows very small oscillations, with can be attributed to modifications of the injection head. The trial evaluation is based on the comparison of the measured pressure and thrust with simulated values. The simulation results presented are the results of a closed loop (with active controller) simulation. The simulation results presented are only for the nominal case.

Figure 7 shows three photos taken with the high speed camera, at ignition (upper photo), and after ignition during the trial (lower photo). Figure 9 shows the command, simulated and measured combustion chamber pressure. The measured pressure follows closely the command except for the lower pressure commands (at 25 bar and 12 bar). This is not due to a limitation of the motor design, but due to a predefined corridor for the control valve position

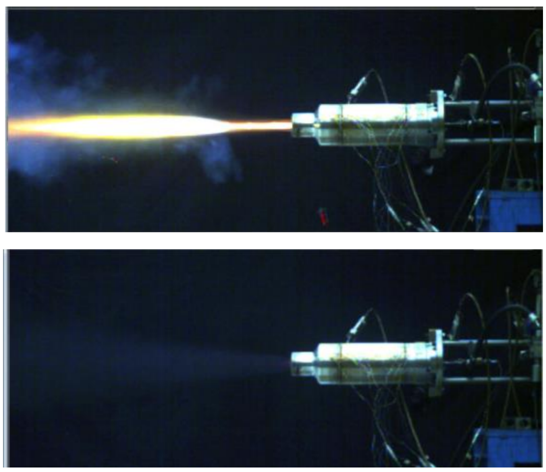

Figure 7: High speed photos during ignition and after ignition end

The measured thrust (Figure 9) follows closely the nominal simulation curve (red line), except for the low pressure steps and the constant pressure command from 33s to 85s. The deviation matches the deviation in the pressure plot. Otherwise, the trial thrust matches closely the expected thrust. The total propellant mass consumption was 30.0 Kg. The theoretical thrust computed from the trial's FMFR is also shown (green line). The differences between theoretical and measured thrust can be explained by different reasons:

- The theoretical thrust does not take into account the wear of the nozzle and of the nozzle throat.

DOI: 10.13009/EUCASS2017-158

– Other transient trial effects are also not taken into account in the theoretical computation of the thrust, like the heat loss to the thermal shield.

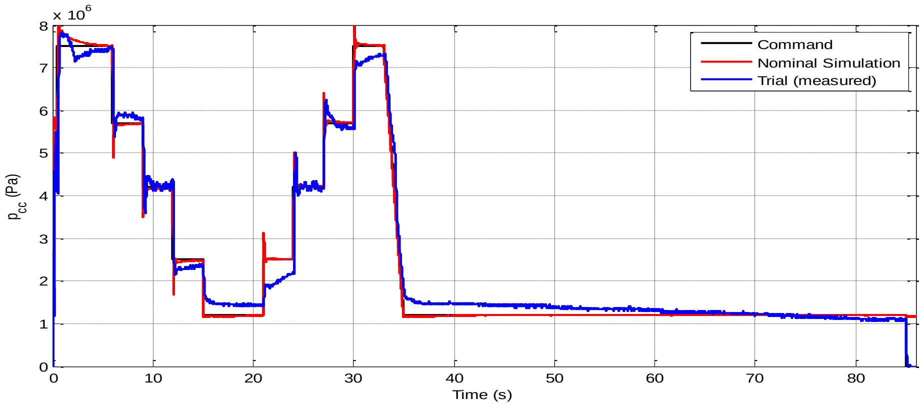

Figure 8: Combustion chamber pressure

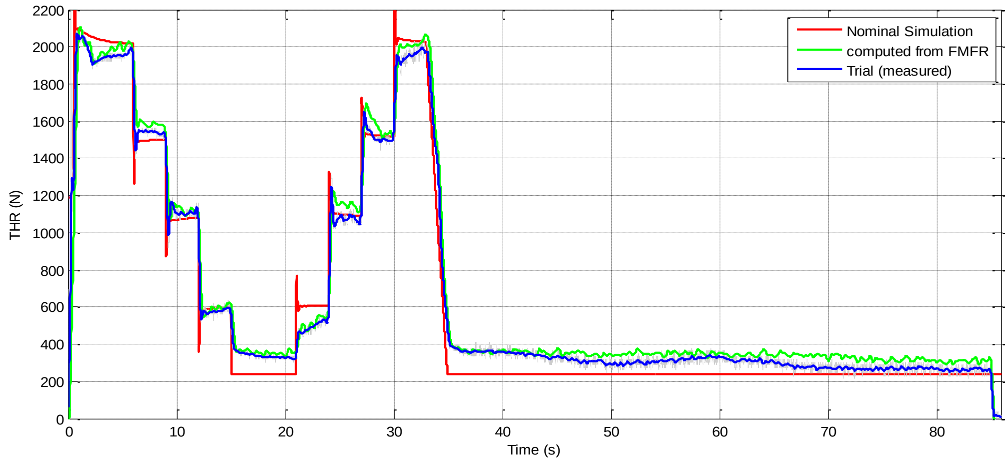

Figure 9: Measured thrust

4.3 20 kN Motor (ACS/DACS exo-atmospheric systems)

Divert-and Attitude Control Systems (DACS) use impulse force to control the trajectory (divert) and the attitude (pich, yaw and roll) of a vehicle flying inside or outside the atmosphere. Vehicles using a DACS system are typically either upper stages of space launchers or anti-ballistic missile effectors, designed to intercept ballistic missiles and their warheads. Figure 10 shows the basic building blocks of a DACS with the exception of the electric energy supply. In most designs a Gas Generator (GG) supplies the gas that is distributed by the nozzle/valve blocks according to the thrust demand. The Divert Control System (DCS) thrusters are arranged around the center of gravity whereas the Attitude Control System (ACS) thrusters are located near the periphery. Usually the maximum thrust level needed for the divert operation is significantly higher than that needed for attitude control. For exoatmospheric interceptor vehicles, the total time of operation of DACS can reach many minutes depending on the mission profile. Within this time, the total time of operation of the DCS, usually consisting of several phases, is much shorter than the total time of operation of the ACS. A detailed overview on the conventional GRM missile configuration is is given in [6].

DOI: 10.13009/EUCASS2017-158

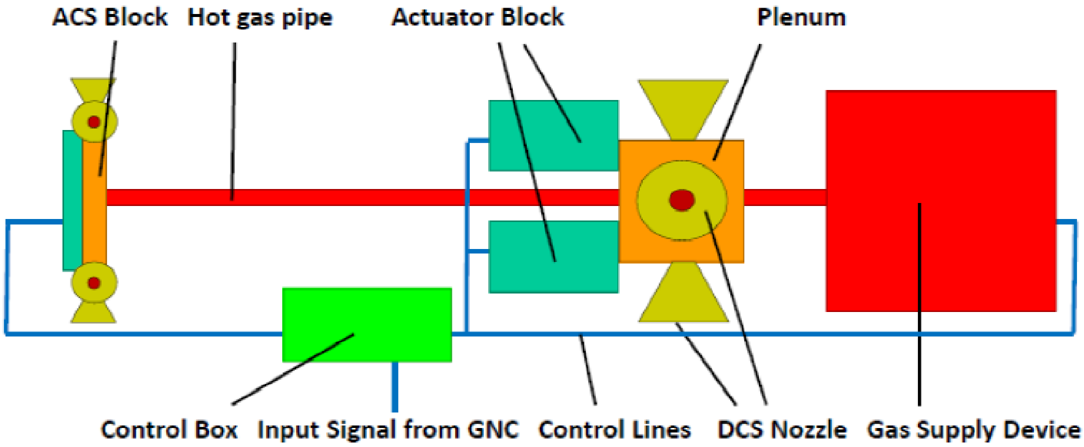

Figure 10: Principle sketch of the main building blocks of a DACS.

Trial GRM-004

A six seconds duration trial of an ACS system can be seen in Figure 11, conducted to evaluate the performance of a GRM ACS system under development at Bayern-Chemie. The nominal PMFR was c.a 3.9 Kg/s. The combustion chamber pressure was 80 bar, stable through the trial, and the ACS controller system executed the commanded thrust perfectly (series of command steps until 4.5 s, sinus of varying amplitude and frequency afterward).

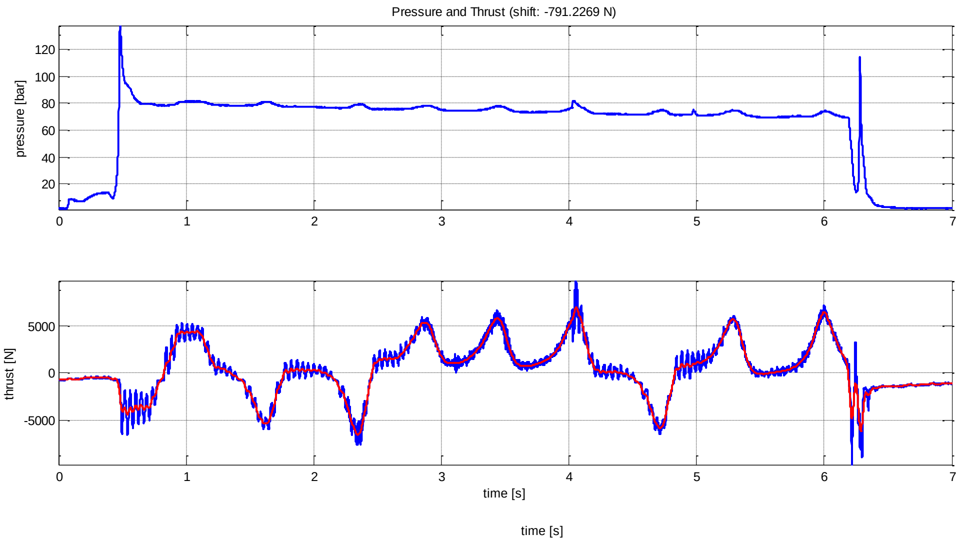

Figure 11a-b: ACS trial combustion chamber pressure (a) and Thrust (b)

5. Conclusion

Gel propulsion systems have the potential to combine easy throttleability with easy handling and storage characteristics. Detailed research and technology development work was conducted within the German Gel Propulsion Technology Program to get a deeper understanding of rheological, flow, spray, combustion and combustor process characteristics. Suitable monopropellant or fuel and oxidizer gels can be fed and sprayed with suitable injectors. With suitable monopropellant gels compact combustor processes even in small model combustors can be realized.

The conducted concept studies show that the GRM technology allows building lightweight rocket motor stages with controllable thrust, low hazard potential and easy handling, transport and storage properties. In order to allow a couple of pulses, a re-ignition capability is under development.

DOI: 10.13009/EUCASS2017-158

Because of the demonstrated very high turn-down ratio of a gel rocket motor with a HCCC, this technology provides a very good gas generator solution for continuously operating ACS and DACS. The very high turn-down ratio minimizes the propellant consumption at the lowest operational point. Furthermore suitable gel propellant compositions allow tailoring the combustion temperature of the GRP to temperature limits that the mechanical part can tolerate for the given mission profile. A concept for a Micro-launcher using green GRM technology for the main propulsion system of all 3 stages is presented in [10].

Current activities aim to improve further the functional and performance parameters. The main goals are:

- To increase I_{spec} and $I_{spec,vol}$ of the monopropellant system
- To develop a re-ignition capability
- To improve the capability for long time operation and to scale the combustor process.

To sum up, despite the realization of a good understanding of gel propulsion relevant processes and of a profound technology base within the German Gel Propulsion Technology Program, there are still gaps to close.

References

[1] Ciezki H.K., Naumann K.W., Weiser V., "Status of Gel Propulsion in the Year 2010 with a Special View on German Activities", *Deutscher Luft- und Raumfahrtkongress 2010*, Hamburg, Germany, August 31 – September 2, 2010

[2] Stierle, R., Schmid, K., Ramsel, J., Naumann, K. W., "Free-Flight Demonstration of the Gelled Propellant Rocket Motor of MBDA-Bayern-Chemie", *4th European Conference for Aeronautics and Space Sciences*, St. Petersburg, Russia, July 4 – 8, 2011

[3] Ciezki, H.K., Negri, M., Gernoth, A., "Advanced Liquid and Gelled Propellants for Rocket and Ramjet Propulsion," Int. Journal of Energetic Materials and Chemical Propulsion, Vol. 14, No. 2, 2015, pp. 85–123

[4] Schmid, K., Ramsel, J., Naumann, K.W., Stierle, R.; Weiser V., "Raketenmotore mit Gel-Treibstoffen – Stand der Technologie bei Bayern-Chemie", *Deutscher Luft- und Raumfahrtkongress 2012*, Berlin., Germany, September 10-12, 2012

[5] Naumann K.W., Ciezki H. K., Stierle R., Schmid K., Ramsel J., "Rocket Propulsion with Gelled Propellants for Sounding Rockets", *20st ESA Symposium on European Rocket and Ballon Programmes and Related Research*, Hyères, France, June 22-26, 2011.

[6] Naumann K. W., Ramsel J., Niedermaier H., Caldas-Pinto P., Hopfe N., Scheutzow S., Riemäcker C. M., Thumann A, "The Application of Rocket Motors and Gas Generators with Gelled Propellants for BMD Interceptors", *AAAF 10th Int. Conf. on Missile Defence*, Mainz, Germany, June 17-20, 2014

[7] Ciezki H.K., Naumann K.W., Weiser V., "Status of Gel Propulsion in the Year 2010 with a Special View on German Activities", *Deutscher Luft- und Raumfahrtkongress 2010*, Hamburg, Germany, August 31 – September 2, 2010

[8] Madlener, K. and H.K. Ciezki. 2009. Some Aspects of Rheological and Flow Characteristics of Gel Propellants with Regard to Propulsion Application. In: *45th AIAA Joint Propulsion Conference*. Paper no. AIAA-2009-5240, August 2-5, 2009, Denver, Colorado, USA.

[9] Sackheim R. L., Masse R. K; "Green Propulsion Advancement: Challenging the Maturity of Monopropellant Hydrazine", AIAA Jourrnal of Propulsion and Power, Vol. 30, N0. 2, pp. 265 – 276, March-April 2014.

[10] K.W. Naumann, H.K. Ciezki, P. Caldas Pinto, J. Ramsel, T. Meyer, S. Rest, A. Thumann, G. Kurth "Green Gelled Propellant Throtteable Rocket Motors for Affordable and Safe Micro-Launchers", *7th European Conference for Aeronautics and Space Sciences*, Milan, Italy, July 3 – 6, 2017