DOI: 10.13009/EUCASS2017-253

Overview on the German Gel Propulsion Technology Activities: Status 2017 and Outlook

H. K. Ciezki[1], C. Kirchberger[1], A. Stiefel[1], and P. Kröger[1],*
P. Caldas Pinto[2], J. Ramsel[2], and K. W. Naumann[2],
J. Hürttlen[3], U. Schaller[3], A. Imiolek[3], and V. Weiser[3]
[*]Corresponding Author, helmut.ciezki@dlr.de, Coordinator of the Scientific/Technical Activities of the German Gel Propulsion Technology Program / Working Group
[1]DLR Institute of Space Propulsion, Lampoldshausen, Langer Grund, 74239 Hardthausen, Germany
[2]Bayern-Chemie GmbH, P.O. Box 1131, 84544 Aschau am Inn, Germany
[3]Fraunhofer Institute for Chemical Technology, Joseph-von-Fraunhofer-Str. 7, 76327 Pfinztal, Germany

Abstract
Gelled propellants are of interest for both rocket and ramjet applications due to the possibility to combine variable "on-demand" thrust control with easy handling and an improved operational safety. Within the German Gel Propulsion Technology (GGPT) working group, which coordinates the common activities of industry, research and the governmental requirements, the necessary technologies to build a green gel propellant rocket engine were developed and its capabilities were demonstrated both by static fire tests and demonstration flights. The paper gives an overview on activities, challenges and findings obtained within the GGPT and it provides an outlook on the current agenda.

1. Introduction

Gelled fluids are homogeneous mixtures of a base liquid and a gelling agent. The beneficial combination of high performance flexibility and superior handling and storage characteristics merge the major advantages of both liquid and solid propulsion systems and can be traced back the non-Newtonian flow behavior of gels. Rocket motors using gelled propellants can be throttled and restarted, similar to engines with liquid propellants. On the other hand, gelled propellants will not spill through leaks, will hardly slosh in the tank and have a reduced vapor pressure in comparison to their base fluid. In this respect gel propellant engines behave like solid-propellant motors.
In the last two decades a growing interest in gelled propellants for rocket and ramjet propulsion applications can be observed worldwide. First work on gel propulsion was already performed in the USA in the 1960s, followed by important contributions in Israel since about mid of the 1990s. In Germany, basic research on green gel propulsion began at the DLR-Institute of Space Propulsion first. Recently, new research was also published in e.g. China, South Korea, India and Japan. Detailed general information about gel propulsion and information about the status of worldwide activities in the year of publication is given in the overview reports in [1] and [2].

1.1 German Gel Propulsion Technology

The German Gel Propulsion Technology (GGPT) working group combines and coordinates the research activities and resources of the partners, namely the Institute of Space Propulsion of the German Aerospace Center (DLR), the Fraunhofer-Institute for Chemical Technology ICT, the Bayern-Chemie, the Bundeswehr Technical Center for Weapons and Ammunition WTD91, and the German Federal Office of Equipment, Information Technology and In-Service Support BAAINBw. When these activities were started, the primary aim was to develop within a first phase the necessary technology to build a gel propellant rocket engine and to demonstrate its capabilities by a demonstration flight within less than a decade. Thereby, basic research activities covered issues such as gel propellant development, rheology, stability and aging as well as the flow, spray and combustion behavior. Based on these activities detailed technology development work has been conducted for the combustor process, the gel rocket

DOI: 10.13009/EUCASS2017-253

engine and its feeding system. Within the initially planned schedule, a throttleable monopropellant GRM was demonstrated in flight in 2009. Details about the free-flight demonstrations are given in [3] and [4]. Key figures of the demonstrator missile are summarized in Table 1 and Figure 1 shows the missile at launch.

Table 1: Key Figures of Gel Demonstrator Missile

Caliber	135 mm
Length	3042 mm
Launch Mass	75 kg
Propellant Mass	12 kg
Nominal Thrust	5.5 kN

Figure 1: The GRM Demonstrator Missile Launch at WTD91 Proving Ground

Since, the work went on to improve the functions and the performance parameters. Ongoing activities comprise the development of new propellant compositions which combine good performance with insensitivity and low environmental hazards as well as an extended operating envelope. Furthermore, the maturing of technologies like the thrust control, the reliable ignition and also re-ignition, the thermal management as well as the deepening of the knowledge on the combustion chamber processes i.e. injection, atomization, evaporation and combustion is on focus. In addition, lightweight materials, optimized design of combustion chambers, and advanced manufacturing methods are investigated for applications requiring a long time of operation and whereas dependable thermal management is necessary.

1.2 Motivation

Gelled monopropellants and bipropellants, i.e. gelled fuels and/or gelled oxidizers, respectively, are interesting candidates for rocket and ramjet propulsion systems because they offer the possibility to build controllable engines with easy handling and storage capabilities. This combines the major advantages of liquid propulsion systems (throttleability) and solid propulsion systems (easy handling, etc.) and is caused by the strongly non-Newtonian flow behavior of the gels.

In common, all kind of gel rocket motors feature the ability to control the thrust. They have a low plume signature when metal or inert particles are not added in the gel composition. Also, the density and energy content may be increased without the risk of sedimentation by adding metal particles. Within the scope of the GGPT development activities it could be shown that gel propulsion systems offer highest potentials to fulfill the development targets of insensitivity, easy handling, transport and storage as well as environmental friendliness of both propellant and exhaust gas [3].

From a system point of view, another reason to develop the gel technology is the intrinsic operational safety of a gel rocket motor (GRM). Three independent functions are necessary to put a GRM into operation i.e. pressurization of the propellant tank, the initiation of the igniter and the opening of the main gel control or on-off opening valve. Even if all of these functions but one is set accidently into operation mode, the GRM will still not unintentionally work. Hence, a specific safety and arming unit (SAU) as typical for solid rocket motors (SRM) is not needed. It is also easy to stop the action by either shutting off the gel valve or venting, i.e. de-pressurization of the gel propellant tank, if the operation or launch process has to be stopped.

DOI: 10.13009/EUCASS2017-253

Comparing a GRM to a SRM it has to be mentioned that the lower density of non-metallized gelled propellants requires a larger volume of the tank and the system becomes more complex since more components i.e. the tank, pressurization, gel flow control device and combustion chamber are needed. Furthermore, the specific impulse of a typical GRM is lower than the one of a liquid rocket motor (LRM) using cryogenic bipropellants e.g. LCH4/LOX but comparable to common storable propellants. However, the hazard potential of a GRM is at the same or even lower level of system complexity significantly lower in the event of an accident or a leakage. Although hybrid rocket motors (HRM) also show some basic features of GRM [6], the process of fuel dissociation on the surface of the solid fuel grain, the mixing with oxidizer and combustion in a highly non-linear, turbulent and three-dimensional flow in the HRM is critical and limits combustion efficiency and controllability. Subsequently, the volume needed for mixing and combustion is in HRM with classical fuels much larger than the volume of the combustion chamber of a GRM that produces the same thrust. Moreover, the storable liquid oxidizers of HRM (except N_2O) are aggressive and have an elevated hazard potential in case of accidents or mistaken handling. A comparison of advantages and disadvantages of different chemical rocket propulsion systems is presented in [7].
Based on these characteristics and as further outlined in e.g. [8] and [9], the technology developed for gel propulsion systems and gelled propellant gas generators (GGG) in Germany has following benefits compared to SRM, LRM and partly HRM technology:

- Low hazard potential, good handling, transport and storage properties, and environmentally friendliness of the propellant and combustion products. Especially the replacement of toxic and potentially dangerous propellant components like hydrazine, nitric acid and ammonium perchlorate is worth mentioning [10].
- The lowest cost of the launch package as the combination of cost for stage, handling and transport. The cost of propellant is usually a major contributor for the total cost of a rocket stage.
- Thrust adaptation, thrust control or thrust termination as means to adapt the trajectory to specific requirements of payloads or if airspace limitations dominate the motor design.

In this respect, GRM and GGG should also be of particular interest for affordable and controllable stages of sounding rockets, propulsion systems for lander vehicles that land on planetary objects without an atmosphere supporting deceleration, apogee motors for orbital insertion or highly controllable rocket motors for active debris removal tug vehicles [11].

2. Gelled Propellants

For the development of gel propulsion systems a very detailed knowledge of the rheological and physical properties and of the flow and spray behavior is essential. The processes are more complex than in common Newtonian propellants and thus demand very intense research activities. The following sub-chapters give a very short overview of these areas with some major results already obtained in the GGPT as well as the current aims of work.

2.1 Composition and Characteristics

An important element of the German approach is the use of propellants that do not exhibit any danger to the staff in case of an accident or destruction, and the same holds for the exhaust gas. In consequence, the German gelled propellants are “green” propellants that are storable over long times under ambient pressure and temperature conditions. Neither the propellants nor the reaction products are toxic or corrosive. Other key requirements on the German GRM technology from the beginning have been:

- Good storability without degradation.
- High degree of insensitivity.
- Wide temperature range both for storage and operation.

For the production of a gel a base liquid is compounded with a gelling agent. In case of organic gellants the preparation of the gels is often very easy, because most gellants can be applied to the liquid by a simple stirring process. For dispersed systems a good dispersion and agglomeration of the solid particles is necessary. This can be achieved for example with special dissolver mixing devices or by ultrasonic treatment. Additives may be used to prevent agglomeration, to improve chemical and physical stability, improve performance and to modify combustion characteristics like the ignition pressure and temperature.
In the first phase of the GGPT mainly gelled monopropellants were investigated. For the selection of suitable gel propellant candidates reasonable performance, manufacturing, handling and treatment properties already existed or have been developed. Gelling agents as organic gellants (gelatine, agar, etc.) or inorganic particles (Aerosil, Cabosil, etc.) have been tested [12][13]. By the addition of metal particles (e.g. Al) or other energetic materials the propellant

density and the combustion temperature and thus specific impulse may be increased [14]. However, tests at ramjet-relevant conditions showed that there may hardly be a positive influence of finer grained Al particles on the combustion efficiency since the oxidation of aluminum is limited under the experimental conditions of the setup [15].
In the second phase of the GGPT monopropellant gels with energetic gellants or gelators that burn signature-free have been investigated. Therefore, the inert gellants have mainly been replaced by carbon and a commercial urea-based gellant and the admixtures were reduced to less than eight percent. The resulting “2nd generation” gels feature both high performance and good delivery characteristics at acceptable storage and safety specifications.
A current object of research is also the development of extremely insensitive monopropellant gels suitable to fulfil even the most demanding requirements on insensitive munition and featuring a wide operational range. In this context, non-energetic and energetic ionic liquids are of special interest. In contrast to the “2nd generation” gels, with mixtures of energetic ionic liquids increased burning rates and glass transition temperatures below -50°C can be achieved. Other properties such as viscosity or insensitivity can be adjusted by adding small amounts of other fuels.
Also bipropellants and especially green hypergolic systems are moving more and more into focus, which could further increase the performance and simplify the ignition process opening up new applications. At present, different oxidizer gels basing on e.g. hydrogen peroxide and ammonium dinitramide (ADN) and ammonium nitrate (AN) are evaluated at laboratory scale [16]. This mixtures feature low glass transition temperatures and reliable storage times. Depending on the fuel (e.g. an energetic ionic liquid) specific impulses of more than 2600 Ns/kg and ignition delay times below 20 ms were achieved. Hot fire tests are scheduled for early 2018 at the latest.

2.2 Physical and Rheological Behavior

From a rheological point of view a gel can be defined as a viscoelastic shear-thinning fluid with a storage modulus higher than its loss modulus if exposed to oscillatory conditions. From an application point of view with respect to rocket and ramjet propulsion, the gelled propellant should behave similar to a solid under storage conditions and similar to a liquid when a sufficiently high shear stress is applied, whereas the gel should be easily sprayable to small droplets and not too high feeding pressures should be necessary.
In general, gels can be described as shear-thinning non-Newtonian fluids with a distinct yield stress. Thereby, the shear thinning behavior is significant and the dynamic shear viscosity η decreases by several decades within technical relevant ranges of the shear rate $\dot{\gamma}$. At high shear rates typical for injection processes the shear thinning behavior diminishes due to the destruction of the gellant structure and leads to a constant viscosity value η_∞, which is called the upper Newtonian plateau. The yield stress τ_0 marks the limit where the gel no longer behaves like an elastic solid but starts to behave like a viscous fluid. The aspect of the rheological behavior of a gel, i.e. shear-thinning, upper Newtonian plateau and yield stress, can be described by the Herschel-Bulkley Extended (HBE) equation, as given in Eq. 1 [17][18].

$$\eta_{HBE} = \frac{\tau_0}{\dot{\gamma}} + K\dot{\gamma}^{n-1} + \eta_\infty \qquad \textbf{(1)}$$

This equation describes the dependence of the shear viscosity on the shear rate with a satisfying accuracy in the whole propulsion relevant shear rate range.

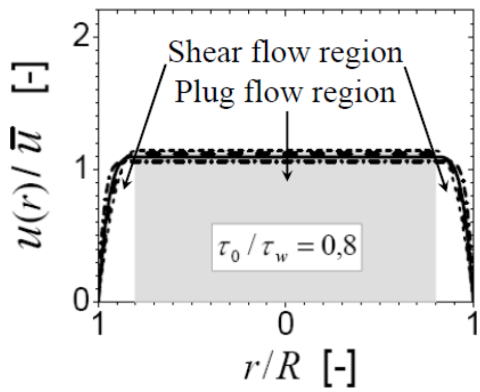

Figure 2: Dimensionless Laminar Velocity Profiles in Tubes for Four Different Gel Test Fuels [19]

DOI: 10.13009/EUCASS2017-253

The flow behavior of non-Newtonian fluids shows several differences to Newtonian fluids. Newtonian fluids have a parabolic velocity profile for flows through tubes of constant diameter under laminar, fully developed, incompressible and steady state conditions. In contrast, shear-thinning fluids show a “broader” velocity profile with lower dimensionless velocities at the centerline (local velocity $u(r)$ divided by average flow velocity $\bar{u}$) and steeper gradients near the tube wall. A flow region with a constant velocity in a distinct area of the tube cross section around the tube centerline occurs, which is caused by shear stresses being lower than the yield stress of the fluid (cf. Figure 2). The size of this plug flow region depends on the ratio of the yield stress to the stress at the wall τ_0/τ_W. For lower stress ratios τ_0/τ_W or higher $\bar{u}$ the plug flow region gets smaller.
This distinct flow behavior has to be considered for the design of feed pipes, injector and valves and also affects the heat transfer and heat transport properties. An ongoing field of investigation is the characterization of the flow field and the pressure losses of gel flows as a function of geometry and rheological properties as well as the thixotropy i.e. time-dependent shear thinning behavior. Therefore, a new experimental setup has been designed and manufactured.

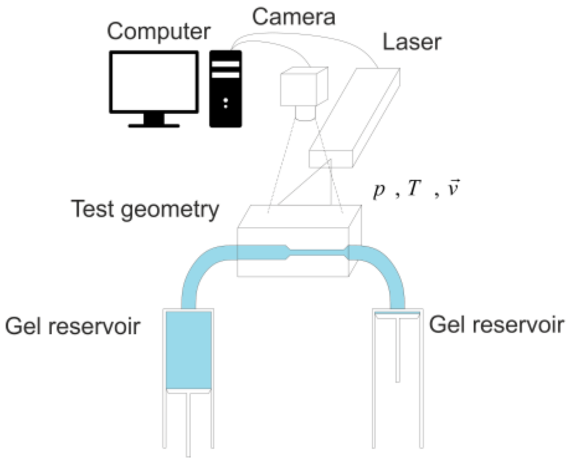

Figure 3: Experimental Setup for Characterization of the Flow Field of Gelled Fluids

Figure 4: A Test Geometry Made of Acrylic Glass

The setup as depicted in Figure 3 consists of two metallic cylinders used as gel reservoirs and an exchangeable test geometry. During the test, the gelled fluid is fed from one cylinder to the other using a hydraulic drive. Thereby, the gel passes the test segment equipped with pressure and temperature sensors. The segment is made of acrylic glass enabling the visual investigation of the gel flow (cf. Figure 4). Due to material incompatibilities with one of the transparent test gels, all metal parts in contact with the gel were coated with a plastic resin. Details on this work are presented in Ref. [20].

DOI: 10.13009/EUCASS2017-253

2.3 Injection and Spray Behavior

It was found that with increasing injection velocities the droplet diameter usually decreases and sufficiently small droplets can be reached. In fact, the spray behavior of the investigated gels is predominantly similar to that of the Newtonian base fluids. However, a detailed investigation was conducted about the origins of the different spray behavior of some gels. The fragmentation of a flowable propellant into small droplets and therewith a high free surface of the droplet ensemble is favorable and even mandatory for a quick conversion of the propellant within a small combustor. Some gels, however, cannot be sprayed to small droplets, but large threads are produced instead (cf. Figure 5). It could be shown that this behavior is caused by viscoelastic effects. Detailed information is given e.g. in Ref. [21].

Figure 5: Comparison of Droplets and Threads Formation for different Gel Compositions [22]

While investigations on the spray behavior have mostly been performed at ambient or low pressure only in the past, tests on spray formation and combustion at high pressures are pursued. Preliminary tests already demonstrated the feasibility and the benefits of a visual examination of the gel injection and combustion using e.g. shadowgraph technique (Figure 6). Experiments with a new model rocket combustor featuring optical access were successfully conducted recently (cf. section 2.4). Additionally, a distinct spray chamber is under design.

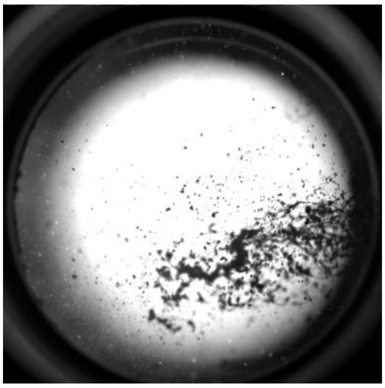

Figure 6: Visual Examination of the Gel Injection within a Pretest

2.4 Combustion Characteristics

Numerous hot fire tests were conducted with a 2nd generation gelled monopropellant using single element model combustion chambers with inner diameter between 20 mm and 50 mm (cf. Figure 7). Seeking for the optimum ratio of combustion chamber volume and nozzle throat area V_c/A_t, also known as the characteristic length $L*$ of the combustor, the combustion chamber length was systematically reduced from 400 mm down to 80 mm, which is equivalent to a variation of $L*$ between 1 m and 7 m taking into account the different nozzle configurations applied.

DOI: 10.13009/EUCASS2017-253

The combustion performance or efficiency of each combustor has been evaluated using the definition of the experimental characteristic velocity c^*, as given in Eq. 2.

$$c^*_{Test} = \frac{p_c \cdot A_t}{\dot{m}} \tag{2}$$

By comparing the experimental c^*_{Test} to the theoretic or ideal c^*_{theo} the combustion efficiency η_{c^*} may be established.

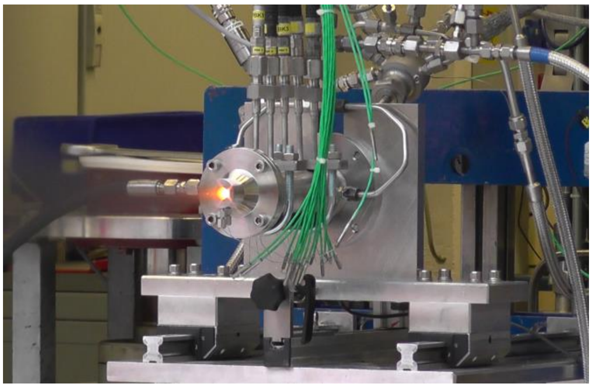

Figure 7: Hot Fire Experiment of a Single Element Gel Combustion Chamber at DLR Test Bench M11.4 in Lampoldshausen

For a small inner diameter i.e. 20.6 mm (BK20.6), a self-sustaining combustion was found with an initial test configuration of L*=7 m and approx. 30 bar as well as for very small characteristic lengths of about 1.3 m when operated at minimum pressure of 40 bar [23]. Thereby, the maximum combustion efficiency of the combustion chamber BK-20.6 has been achieved for a chamber length of 150 mm up to 180 mm, which equals a characteristic length L* of 1.5 m to 2 m. This finding is also shown in Figure 8.

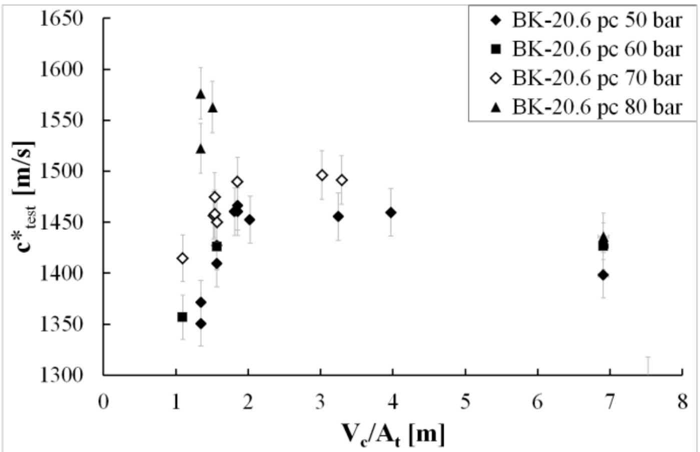

Figure 8: Experimental Characteristic Velocity c* versus Characteristic Length V_c/A_t and Combustion Pressure p_c for Combustion Chamber BK-20.6

In comparison, hot fire tests with the combustion chambers with the largest inner diameter of 50 mm showed generally lower combustion efficiency with an optimum characteristic length of approx. 7.5 m but with a more extensive operational pressure range. Additional tests with combustion chambers with inner diameter of 20 mm, 30 mm and 40 mm and a fixed characteristic length revealed a strong link between a self-containing combustion, combustion efficiency and the spray-wall interaction. For a sufficiently heated chamber wall the combustion efficiency can be significantly boosted by a smaller combustion chamber diameter since the heat transfer to the propellant deposed on the wall will be increased. However, the deposition of large amounts of unburnt gelled propellant on the cold wall during startup makes it more unlikely to establish a self-contained stable combustion. The exact correlations are currently under evaluation.

DOI: 10.13009/EUCASS2017-253

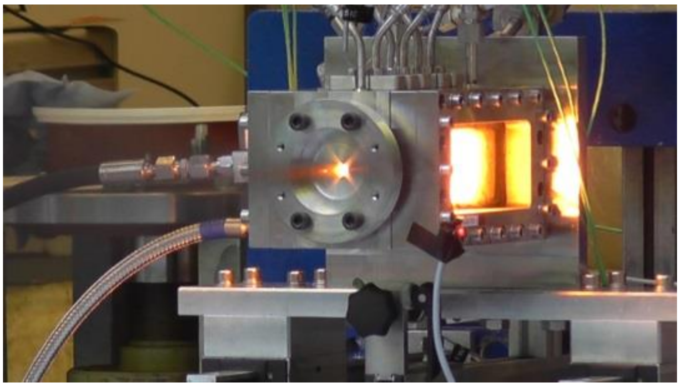

Figure 9: Hot Test of Gel Combustion Chamber Featuring Optical Access at DLR Test Bench M11.4

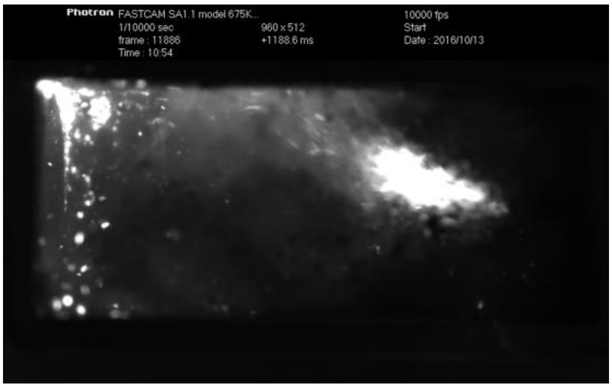

Figure 10: Ignition of Gel Propellant during Startup Phase (Still from High Speed Video)

Experiments with a new model rocket combustor featuring optical access as shown in Figure 9 have started. Ignition and run-in tests with the combustion chamber using dummy windows were successfully performed and demonstrated the safe and reliable operation of igniter, injector, purge as well as the measurements and DAQ system. Using both standard and high speed video sets feasibility tests on different video and filter settings have been performed. Thereby, first focus was set on the ignition and startup processes for the gelled propellants under investigation (cf. Figure 10). Details on these experiments are given in Ref. [24].

3. System Demonstration and Engine Development

While bipropellants and hypergolic gel propellants are a subject of current technology work, the monopropellant GRM and GGG systems that fulfil the requirements have by now been developed to a state that allows entering into the development of operational systems. The status as well as current and future development objectives are presented in this section.

3.1 Status of Development

In addition to the aforementioned properties common to all GRM developed within the GGPT, the current monopropellant GRM and GGG development has successfully shown:

- A family of GRP with different fuel blends, gelling agents, additives and particles that covers a wide range of propellant properties in terms of specific impulse, density, combustion temperature and combustion pressure range, as shown in Table 2.
- Very stable start, combustion and throttling behavior of the motors and gas generators.

DOI: 10.13009/EUCASS2017-253

- Very wide turn-down range in terms of FMFR; ratios of 15:1 with fixed nozzle and 50:1 with variable throat nozzle and variable injector elements have been successfully tested [25]. Figure 11 shows such a static test GRM with variable nozzle throat.
- Implementation of effective control methods has been shown [26][27][28]. In Figure 12 simulated/predicted (green) and hot fire data (blue) of a test with variable throat nozzle is depicted. In this test thrust has been varied while the combustion pressure has been kept constant at 5 MPa.
- Very good scalability of size beyond nominal (= full) thrust of 300 N to 20 kN has been demonstrated.
- No or little primary and secondary smoke is visible if no solid additives are used.
- Good handling, transport and storage properties.
- Wide operational temperature with a range from at least -30°C to +70°C.
- Ignition by a solid propellant igniter or a gas burner.
- Lower costs for the gel propellant compared to solid propellant or other storable propellants.
- Long running operation; an operation time of 85 seconds has already been demonstrated, and the expertise of the GRM used showed that for the operating conditions used this motor has the potential to operate for about 3 minutes [29].

Table 2: Specific Impulse, Combustion Temperature and Density of Various Gelled Monopropellants [25]

Gel	I_{sp} **[Ns/kg]** **(p_c/p_∞=70)**	T_c **[K]**	**ρ [g/cm³]**
GRP 001	2194	2144	1.13
GRP 002	2512	2795	1.31
GRP 003	2236	2089	1.18
GRP 004	2586	2910	1.28
GRP 005	2080	1883	1.17
GRP 006	2182	1981	1.16
GRP 007	1900	1396	1.11
GRP 008	1878	1375	1.09
GRP 009	2143	1904	1.19
GRP 013	2290	2536	1.41
GRP 014	2178	1857	1.14
GRP 015	2467	2770	1.38
GRP 016	2465	2809	1.38
GRP 017	2423	2650	1.38
GRP 018	2135	2574	1.42
GRP 019	1990	1438	1.11
GRP 025	2588	3080	1.49
GRP 026	2622	3150	1.49
GRP 039	2629	3180	1.55

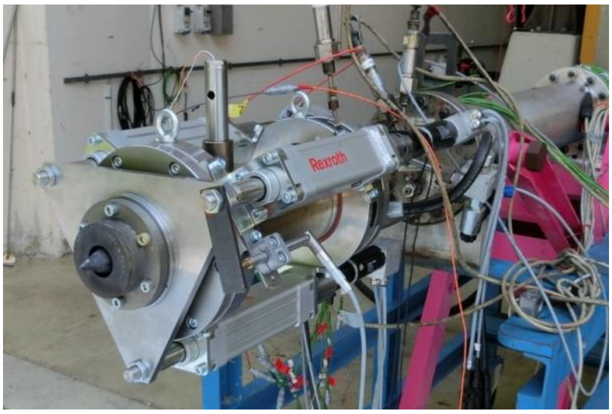

Figure 11: GRM with Variable Throat Nozzle. Engineering Setup for Static Tests

DOI: 10.13009/EUCASS2017-253

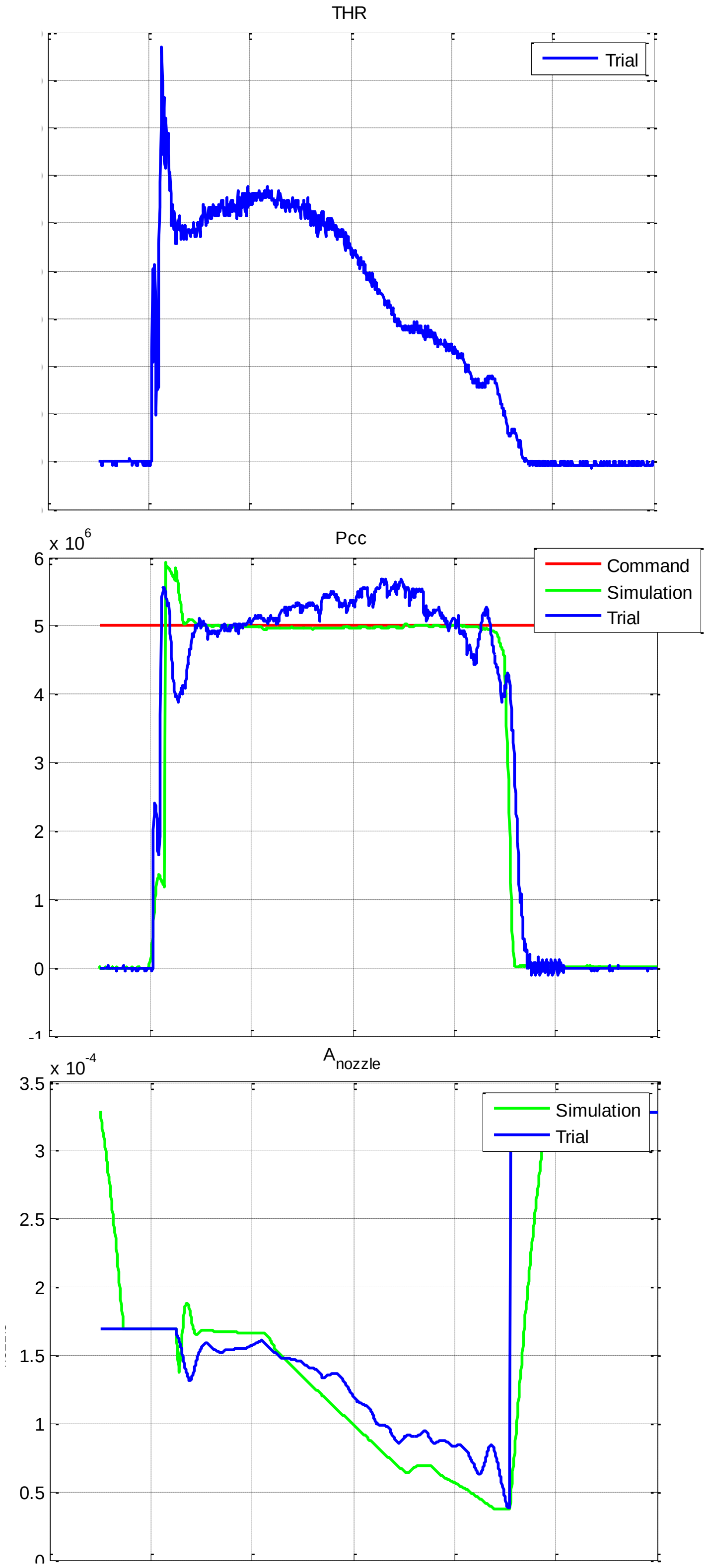

Figure 12: Thrust, Combustion Pressure and Control Signals of a GRM Test [25]

DOI: 10.13009/EUCASS2017-253

3.2 Current and Future Development Activities

One main objective of the current activities is to improve the performance of the gel propellants i.e. development of a "3rd generation" gel propellant family. Thereby, the goals comprise e.g. the reduction of the lower temperature limit of operation and the further increase of both mass and volume specific impulse. The development of a bipropellant gel propellant system which is ideally both green and hypergolic is an important area of research. In order to compensate the higher complexity compared to a monopropellant system, the ballistic performance of such bipropellant system needs to be significantly better.
Although some preliminary tests have already been performed successfully, a re-ignition capability for monopropellant GRM has to be developed and demonstrated if required so by the mission.
The efficiency of the combustion process will be improved in order to minimize the size and weight of the combustion chamber. Here, enhanced injector element designs derived from the visual examination of the spray patterns, the evaporation and the combustion of the gel propellant (cf. section 2.4) may be taken into account. Also the findings from the comprehensive investigation on the influence of the combustion chamber geometry will be considered.
Longer operation times have to be verified. In this context, the thermal management, the overall combustion chamber design and the utilization of new and advanced materials and manufacturing methods e.g. additive layer manufacturing (ALM) and ultra-high temperature ceramic matrix composites (UHTCMC) will be screened.
Because of the very high modularity of the GRM, future improvements can be integrated into existing systems as soon as these features are mature enough for application.

4. Conclusion and Outlook

Gel propellants offer the possibility to realize propulsion systems, which are easy to throttle and which have simple handling and storage characteristics. The joint research and technology development activities of the German Gel Propulsion Technology working group led to a thorough understanding of the functions and system aspects of gel rocket motors and gel gas generators. The improvement of the performance characteristics of the gel propulsion technology with the scope to various applications and gel motor types is the main focus of the ongoing activities.
Up to now the understanding of basic processes as well as the knowledge about combustor and engine technology on gel propulsion has significantly been improved and the gel propulsion technology developed within the GGPT is ready for first applications. Open issues and potentials for improvement have been identified and are object of current or intended work.

Acknowledgment

The authors would like to thank their colleagues, who work in the German Gel Propulsion Technology working Group, for the good collaboration and the conducted work. The financial support to the work on gel propulsion by the German MoD's Federal Office of Equipment, Information Technology and In-Service Support (BAAINBw) is kindly acknowledged.

DOI: 10.13009/EUCASS2017-253

Nomenclature

Latin

A	[m^2]	Area
c^*	[m/s]	Characteristic Velocity
I_{sp}	[N·s/kg]	Specific Impulse
K	[Pa·s^n]	Parameter of HBE Equation
L^*	[m]	Characteristic Length
$\dot{m}$	[kg/s]	Mass Flow Rate
n	[-]	Exponent of HBE Equation
p	[Pa]	Pressure
T	[K]	Temperature
THR	[N]	Thrust

Greek

$\dot{\gamma}$	[s^{-1}]	Shear Rate
η	[Pa·s]	Dynamic Shear Viscosity
η_{c^*}	[-]	Combustion Efficiency
η_∞	[Pa·s]	Apparent Dynamic Shear Viscosity at Newtonian Plateau
ρ	[kg/m^3]	Density
τ	[Pa]	Shear Stress
τ_0	[Pa]	Yield Stress

Indices

c	Combustion Chamber
t	Throat
test	Experimental
theo	Theoretical
w	Wall
∞	Ambient Conditions

Abbreviations

ALM	Additive Layer Manufacturing
CC	Combustion Chamber
FMFR	Fuel Mass Flow Rate
GGG	Gelled Propellant Gas Generator
GGPT	German Gel Propulsion Technology Program
GRM	Gel Rocket Motor
GRP	Gel Rocket Propellant
HBE	Herschel-Bulkley Extended
HRM	Hybrid Rocket Motor
LRM	Liquid Rocket Motor
SAU	Safety and arming unit
SRM	Solid Rocket Motor
UHTCMC	Ultra-High Temperature Ceramic Matrix Composites

DOI: 10.13009/EUCASS2017-253

References

[1] Natan, B., and Rahimi, S. (2001). The Status of Gel Propellants in Year 2000. *Combustion of Energetic Materials*, edited by Kuo, K.K., and DeLuca, L.T., Begell House, New York, pp. 172–194.

[2] Ciezki, H.K., Naumann, K., and Weiser, V. (2010). Status of Gel Propulsion in the Year 2010 with a Special View on the German Activities. Paper No. 1326. Deutscher Luft- und Raumfahrtkongress 2010, Hamburg, Germany.

[3] Stierle, R., Schmid, K., Ramsel, J., Naumann K.W. (2011). Free-Flight Demonstration of the Gelled Propellant Rocket Motor of MBDA Bayern-Chemie. Proceedings of 4th European Conference for Aerospace Sciences (EUCASS), St. Petersburg, Russia.

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

[5] Ciezki, H.K., Negri, M., Hürttlen, J., Weiser, V., Naumann K.W., Ramsel, J. (2014). Overview of the German Gel Propulsion Technology Program. AIAA-2014-3794, Proceedings of 50th AIAA/ ASME/ SAE/ ASEE Joint Propulsion Conference, Cleveland, OH, USA

[6] Chiaverini, M.J., Kuo, K. (2007). Fundamentals of Hybrid Rocket Combustion and Propulsion. In: *Progress in Astronautics and Aeronautics*, Vol. 218, AIAA.

[7] Ciezki, H.K., and Naumann, K.W. (2016). Some Aspects on Safety and Environmental Impact of Gel Propulsion. Propellants, Explosives, Pyrotechnics, invited publication for special issue *Insensitive Munitions*, Vol. 41 (3), pp. 539-547.

[8] Naumann, K.W., Stierle, R., Schmid, K., Ramsel, J. (2012). Rocket Motors Burning Gelled Propellants - Potential Applications for Space Propulsion. Deutscher Luft- und Raumfahrtkongress 2012, Berlin., Germany.

[9] Naumann, K.W., Ramsel, J., Caldas-Pinto, P., Niedermaier, H., Thumann, A. (2014). Gelled Green Propellant Rocket Motor and Gas Generator Technology at Bayern-Chemie – Status and Applications for Space Systems. AIAA-2014-3796, Proceedings of 50th AIAA/ ASME/ SAE/ ASEE Joint Propulsion Conference, Cleveland, OH, USA.

[10] Sackheim, R.L., Masse, R.K. (2014). Green Propulsion Advancement: Challenging the Maturity of Monopropellant Hydrazine. AIAA *Journal of Propulsion and Power*, Vol. 30, No. 2, pp. 265–276.

[11] Naumann, K.W. et al. (2016). Green, Highly Throttleable Gelled Propellant Rocket Motors – State and Application Potentials. Paper ID 3124831, Proceedings of 5th Space Propulsion Conference, Rome, Italy.

[12] Bohn, M.A., Hürttlen, J., Menke, K., Roth, E., and Weiser, V. (2008). Entwicklung und Charakterisierung umweltfreundlicher Geltreibstoffe für schubgeregelte Raketenantriebe. Deutscher Luft- und Raumfahrtkongress 2008, Darmstadt, Germany.

[13] Louaze, G., Caty, F., Weiser, V., and Roth, E. (2007). Influence of Aerosil on the combustion of gelled nitromethane. Proceedings of *38th Int. Annual Conference of ICT*, Karlsruhe, Germany, pp. 92/1-92/11.

[14] Tepper, F., and Kaledin, L. (2000). Combustion characteristics of kerosene containing Alex® nano-aluminum. Proceedings of the *5th Int. Symposium on Special Topics in Chemical Propulsion* (5-ISICP), Stresa, Italy.

[15] Negri, M., and Ciezki, H.K. (2015). Combustion of Gelled Propellants Containing Microsized and Nanosized Aluminum Particles. AIAA *Journal of Propulsion and Power*, Vol. 31, No. 1, pp. 400–407.

[16] Weiser, V., Hürttlen, J., Schaller, U., Imiolek, A., and Kelzenberg, S. (2017). Green Liquid Oxidizers Basing on Solutions of ADN and AN in Hydrogen Peroxide for Hypergolic Propellants with High Performance. Paper 364, To be presented at 7th European Conference for Aeronautics and Space Sciences (EUCASS), Milan, Italy.

[17] Madlener, K., and Ciezki, H.K. (2005). Theoretical Investigation of the Flow Behavior of Gelled Fuels of the Extended Herschel-Bulkley Type. Proceedings of 1st European Conference on Aerospace Sciences (EUCASS). Moscow, Russia.

[18] Ciezki, H.K., Kröger, P., Negri, M. (2015). Influence of Various Aspects on the Performance Characteristics of Gel Propulsion Systems. Proceedings of 6th European Conference for Aeronautics and Space Sciences (EUCASS), Krakow, Poland.

[19] Madlener, K., and Ciezki, H.K. (2012). Estimation of Flow Properties of Gelled Fuels with Regard to Propulsion Systems. *Journal of Propulsion and Power*. Vol. 28, No. 1, pp. 113–121.

[20] Stiefel, A., Kirchberger, C., Ciezki, H.K. (2017). Design and Realization of a Test Stand for Optical Fluid Dynamic Research of Gels. Paper 216, To be presented at 7th European Conference for Aeronautics and Space Sciences (EUCASS), Milan, Italy.

[21] Negri, M., Ciezki, H.K., and Schlechtriem, S. (2013). Spray behavior of non-Newtonian fluids: correlation between rheological measurements and droplets/threads formation. *Prog. Propuls. Phys.*, Vol. 4, pp. 271–290.

[22] Ciezki, H.K. and Negri, M. (2013). Overview on Gel Propulsion Activities at DLR Institute of Space Propulsion. Proceedings of 5th European Conference for Aeronautics and Space Sciences (EUCASS), Munich, Germany.

DOI: 10.13009/EUCASS2017-253

[23] Kröger, P., Kirchberger, C., and Ciezki, H.K. (2016). Influence of the Combustion Chamber Geometry on the Performance of a Gel Propulsion System. ID 3124841, Proceedings of 5th Space Propulsion Conference, Rome, Italy.
[24] Kirchberger, C., Ciezki, H.K., Kröger, P. (2017). Realization and Run-In of a Gel Combustion Chamber with Optical Access. Paper 250, To be presented at 7th European Conference for Aeronautics and Space Sciences (EUCASS), Milan, Italy.
[25] Ramsel J., Scheutzow S., Caldas-Pinto P., Naumann K.W., Thumann A., Kurth G. (2015). Gelled Rocket Propellants – Development and Performance. Proceedings of 6th European Conference for Aerospace Sciences (EUCASS), Krakow, Poland.
[26] Caldas-Pinto, P., Ramsel, J., Scheutzow, S., Naumann, K.W., Thumann, A., Kurth, G. (2015). Control Characteristics of a Gel Propellant Throttleable Rocket Motor. Proceedings of 6th European Conference for Aeronautics and Space Sciences (EUCASS), Krakow, Poland.
[27] Caldas-Pinto, P., Ramsel, J., Niedermaier, H., Thumann, A., Naumann, K.W. (2014). Control Characteristics of a Gelled Propellant Throttleable Rocket Motor With a Pintle Nozzle. AIAA-2014-3797, Proceedings of 50th AIAA/ ASME/ SAE/ ASEE Joint Propulsion Conference, Cleveland, OH, USA.
[28] Naumann, K.W., Caldas-Pinto, P., Ramsel, J., Scheutzow, S., Thumann, A., Niedermaier, H., Hopfe, N., Kurth, G. (2015). Gelled Propellant Throtteable Rocket Motor and Gas Generator Technology at Bayern-Chemie. Proceedings of 6th European Conference for Aeronautics and Space Sciences (EUCASS), Krakow, Poland.
[29] Caldas-Pinto, P. et al. (2016). Long Duration Trials of a Throttleable Gelled Propellant Rocket Motor. Paper ID 3124980, Proceedings of 5th Space Propulsion Conference, Rome, Italy.