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Realization and Run-In of a Gel Combustion Chamber with Optical Access

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Abstract
Gel propellants offer the possibility to build throttleable propulsion systems with easy handling and storage characteristics. At the German Aerospace Center (DLR) and embedded in the German Gel Propulsion Technology (GGPT) activities basic research and technology development is performed on production, rheological properties, flow behavior, spray characteristics and combustion behavior of gelled propellants. Recently, a new gel combustion chamber with optical access has been deployed. This publication gives a general overview on gel propulsion and provides details of the design and run-in tests of the new combustion chamber.

1. Introduction

Gelled propellants and their specific properties are of interest for both rocket and ramjet applications due to the simplicity of implementing a variable “on-demand” thrust control, easy handling and improved operational safety [1]. The beneficial combination of performance flexibility and storage characteristics merge the major advantages of liquid and solid propulsion systems. This is mainly caused by the non-Newtonian flow behavior of gels. A net-like structure is formed by a gelling agent, in which a liquid – either a monopropellant, a fuel or an oxidizer – is embedded. The gelled fluid behaves like a solid at rest, but once the network structure of the gel is destroyed by a sufficiently high shear stress, the gel is liquefied. At very high shear rates, typically reached during the propellant injection processes, the properties of the gelled liquid become very similar to the properties of the pure liquid itself.

For the development of gel propulsion systems a very detailed knowledge of non-Newtonian rheological and physical properties and of the flow and spray behavior is an essential base. The processes are more complex than in Newtonian propellants and demand thus very intense research activities [2]. The spray behavior of gels seems to be very similar to that of the Newtonian base fluids in most cases. However, a different behavior has been observed for some gels with the formation of large threads instead of small droplets due to viscoelastic effects [3].

At the Institute of Space Propulsion of the German Aerospace Center (DLR) investigations on environment-friendly and simply producible gels with advanced combustion and performance characteristics are conducted. The main goal is to obtain a detailed knowledge of the processes within combustion chamber, injector and feed lines. This shall enable the realization of a reliable design process for future gel rocket motors with high power densities and stable operating envelopes at reduced costs and demand for testing. These investigations are part of the German Gel Propulsion Technology (GGPT) activities and also embedded in the Defence & Security Research at DLR. Information on the GGPT working group is given in e.g. Refs. [4] to [8].

While the investigations with optical analyses have mostly been performed at ambient or low pressure only in the past, currently tests on the spray formation and combustion at high pressures are pursued. Therefor a new gel model rocket combustor featuring an optical access has been deployed. Preliminary tests already demonstrated the feasibility and the benefits of a visual examination of the gel injection and combustion using e.g. shadowgraph technique [7]. This paper will give an overview on design, realization and run-in campaign of the new combustion chamber with optical access as well as first results obtained.

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2. Test Setup

The following section outlines general information on the test complex M11 which provides the laboratory infrastructure and staff for the research efforts on gelled propellants at the German Aerospace Center (DLR) site in Lampoldshausen. Furthermore, the test hardware and the gel propellant used are described.

2.1 Test Facility

The very first part of test complex M11 at in Lampoldshausen was built with two test cells and a small office and laboratory building in 1966 [9]. Since these days the test facility is used to carry out research and test activities in the field of rocket and ram-/scramjet propulsion and has been enlarged and refurbished several times. The test facility is operated by the propellants department of the DLR Institute of Space Propulsion and work is currently focused on research in the area of green advanced propellants, gelled propellants, hybrid propulsion, and scramjet propulsion. Thereby, test activities both for DLR-internally and externally funded projects are performed. The test complex offers also the possibility to conduct contract R&D work for partners from industry, research organizations, universities and agencies.
The test complex M11 consists of four test positions in two test cells (M11.1 to M11.4), the research and student test field (M11.5) and a propellant preparation and production facility (G49). Each test position at the M11 is equipped with newest data acquisition and control systems and enables a specific kind of test conditions while assuring high flexibility. The test facility provides 200 bar gas supply systems for H_2, O_2, N_2 and pressurized air. All the valves and pressure regulators of the test bench are controlled by a redundant Siemens SPS. Additionally each test position features a flexible measurement system optimized for the specific test requirements. This offers the possibility to conduct combustion, flow and spray tests with a wide range of different rocket propellants. Furthermore the simulation of relevant ram-/scramjet combustor entrance conditions or generally the testing of various propulsion hardware components and materials is possible.
The test position M11.4 is exclusively used for investigations on the combustor processes i.e. injection, evaporation and combustion of gelled propellants. The gelled propellants are stored in easy exchangeable piston-type accumulators, so-called cartridges. Using hydraulic drives with a continuously adjustable control, the gels are fed with exact and freely selectable mass flow rates through the feed pipes to the injectors. For a reliable and smooth ignition usually a H_2/O_2 gas torch igniter is used and the combustion start may be boosted by an auxiliary oxygen injection. A 100 l / 10 bar water tank is available for emergency cooling and purging. The test position is also equipped with a high pressure water cooling system providing up to 1.2 m³ H_2O at up to 200 bar although recent research did not make use of the latter infrastructure. A comprehensive measurement instrumentation including thrust, pressures and temperatures as well as optical diagnostics is present. The DAQ system was renewed in 2016 and allows simultaneous acquisition of up to 160 channels. It also features unique capabilities e.g. an integrated test database and redline monitoring.
A set of modular, cylindrical, capacitively cooled combustion chambers with different diameters and lengths has been used for the determination of the characteristic length L* for monopropellant gel under investigation (cf. ref. [10]). Furthermore, two different model combustion chambers with windows allow access for optical diagnostic tools allowing enabling the visualization and investigation of the combustor processes.

2.2 Combustion Chamber Design

Preliminary hot fire tests were performed with a round combustion chamber with an inner diameter of 50 mm where round windows have been installed in tubes on both sides of the chamber (cf. Figure 1). Although these experiments already demonstrated the feasibility and the benefits of a visual examination of the gel injection and combustion, these tests also revealed some drawbacks of the setup used. These are e.g. the very limited field of view, accumulation of unburnt reaction products in the tubes and finally fouling of the windows. Taking into account these experiences a modular rectangular chamber design was favored and a new model rocket combustor was developed and manufactured.

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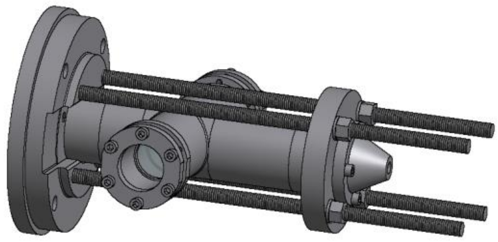

Figure 1: Sketch of gel combustion chamber with round windows used for preliminary tests

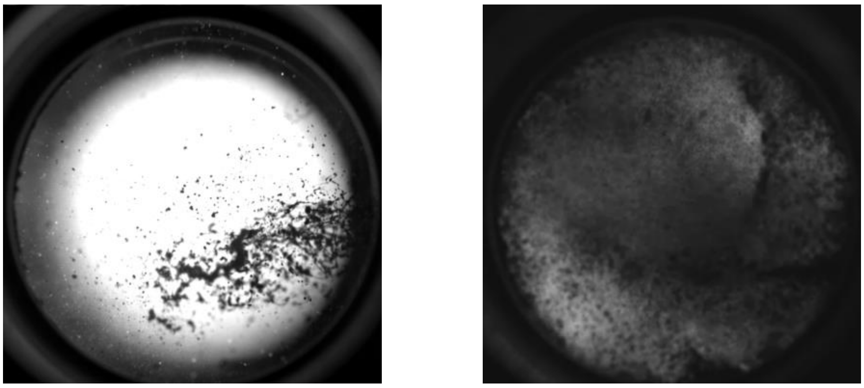

Figure 2: Inition of gel injection (left) and accumulation of combustion products after 1.5 s (right) (snapshot from high speed video of preliminary test)

The combustor as depicted in Figure 3 is made of stainless steel and features both an interchangeable nozzle and a changeable single impinging injector element. Main geometric and design characteristics are given in Table 1. So far, two injector elements with different impingement patterns have been deployed. For the window sapphire was chosen due to its superior mechanical and thermal properties. The sapphire window is preinstalled in a metallic frame simplifying the handling at the test facility and reducing changeover times in between tests. With the exception of a nitrogen purge/ film cooling system for reducing the deposition of soot on the sapphire window and to limit the heat loads during start-up no active cooling is foreseen. Therefore, the test time is limited to a few seconds. Beside several pressure transducers installed along the chamber axis, up to 34 thermocouples in 11 clusters with wall distances of 1, 2 and 3 mm may be installed on the top side allowing a rough map of the injector footprint on the chamber wall. Moreover, the sapphire windows may be replaced by different dummy elements featuring additional thermocouples and enabling various configuration scenarios (cf. Figure 4).

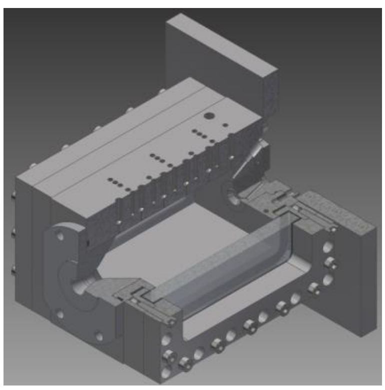

Figure 3: Sketch of new rectangular gel rocket combustion chamber with optical access (3/4 cut-out, simplified)

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Table 1: Main characteristics of new gel rocket combustion chamber with optical access

Dimensions			
Length	L	[mm]	120
Width	W	[mm]	80
Height	H	[mm]	50
Throat Diameter	d_t	[mm]	6; 8; 10
Pressure			
nominal	$p_{c,nom}$	[MPa]	5.0
maximum	$p_{c,max}$	[MPa]	8.0
Characteristic Length	L*	[m]	17; 9.5; 6
Chamber Contraction Ratio	ε_c	[-]	140; 80; 51

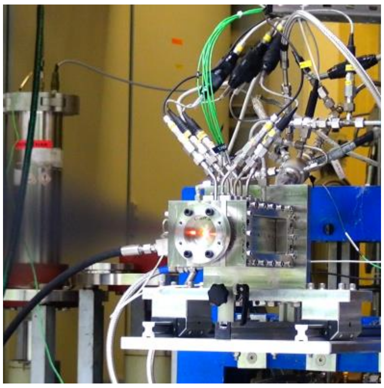

Figure 4: First hot fire test of new gel rocket combustion chamber with optical access (windows replaced by dummies)

2.3 Propellant

An important element of the German approach is the use of propellants that do not exhibit any danger to the personal 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, a high degree of insensitivity and a wide temperature range both for storage and operation.
Currently, gelled monopropellants with energetic gellants or gelators that burn signature-free are investigated. The formerly used inert gellants have been replaced by carbon and a commercial urea-based gellant and the admixtures were reduced to less than eight to ten percent. The resulting "2nd generation" gels feature both high performance and good delivery characteristics at acceptable storage and safety specifications. Thereof, three gels of different compositions or treatment were tested up to now.

3. Test Method and First Results

In this section the general experimental approach and preliminary results from hot fire tests are presented. Furthermore, an overview on first findings from the video analyses is given.

3.1 Test Logic

The modular design of the combustion chamber allows the variation of several dependent and independent parameters characteristic of gel rocket motors. By changing the nozzle, a different characteristic length $L^* = {V_c}/{A_t}$ thus residence time can easily be changed. Within the limits of both the test hardware and the hydraulic drive the

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mass flow rate and consequently the combustion chamber pressure is continuously adjustable. Due to the exchangeable injector element the influence of the injection pattern, injection angle or injection cross-section can be investigated. Furthermore, the combustion chamber might be equipped with metallic dummy windows, sapphire windows on one or both sides or other distinctive test specimen. Finally, also the type and composition of the monopropellant gel can be varied.

The run-in tests with the new gel rocket combustion chamber as well as each test campaign are conducted in a step-by-step approach (see Figure 5). First, ignition and startup tests are performed with window dummies for each new hardware configuration or gel propellant in order to verify reliable ignition and stable operation of the combustion chamber at nominal conditions. Afterwards, the test duration is increased from 3 seconds to 6 seconds and the performance and stability i.e. the minimum combustion pressure are explored. For the run-in campaign also the interference of the gel combustion and N_2 purge has been investigated. Based on the findings of latter tests, the window purge/ cooling is activated during startup and shutdown only but not for the duration of the nominal operation. With the operational envelope known, short time experiments i.e. hot fire tests up to 3 seconds are carried out with the sapphire window installed and at low combustion pressure. Here, some testing has already been done in order to identify proper visual diagnostics, camera settings and, where applicable, appropriate filters. With more confidence in both the optical measurement techniques and the combustion chamber operation procedures longer tests at higher combustion pressures are pursued.

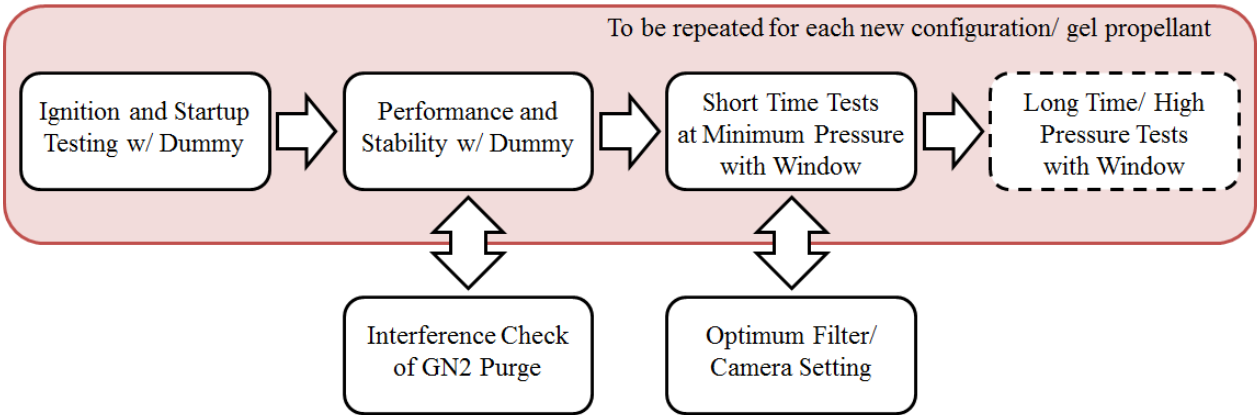

Figure 5: Test methodology for testing the gel rocket combustion chamber with optical access

The initial test setup comprised the 6 mm nozzle and the injector “A”, which is a 2D symmetric injection element, as well as the standard monopropellant gel under investigation, provided by a partner of the GGPT (“Gel A”) and otherwise produced onsite with a similar composition but different treatment (“Gel B”). 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. Set into full operation in August 2016, first experiments with sapphire windows have been performed. However, the findings of these tests e.g. substantial fuel/ soot depositions on the windows recommended the continuing of the experiments with the injector “B” which design is commonly used in gel rocket motors within the GGPT. Recently, a modified gel composition with improved storability (“Gel C”) was introduced.

Up to now, 68 single tests have been conducted, which have been evaluated in general. However, a detailed analysis and comparison with visual information is ongoing.

3.2 Combustion Characteristics and Performance

Although the performance and stability behavior of this model gel rocket combustion chamber might not be representative for flight hardware by absolute numbers, the comparison of different injector elements or gel propellants in conjunction with visual information on the spray pattern and the combustion zone provides valuable data for the design of optimized gel rocket motors.

The combustion performance or efficiency has been evaluated using the definition of the experimental characteristic velocity c^*, as given in Eq. 1. It is calculated from the effective throat stagnation pressure p_c, the minimum thrust chamber area (at the throat) A_t and the mass flowrate at the throat $\dot{m}$.

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$$c^*_{Test} = \frac{p_c \cdot A_t}{\dot{m}} \quad \textbf{(1)}$$

By comparing the experimental c^*_{Test} to the theoretic or ideal c^*_{theo} the combustion efficiency η_{c^*} may be established. Following the JANNAF method [10], corrections for known influences on the measured static pressure, the physical throat area and the mass flow rate should be introduced. Currently, for the stagnation pressure in the throat the static pressure in the combustion chamber is taken. This is a valid simplification since the Mach number in the chamber is very low (≈ 0.003). A big influence factor is the thermal deformation of the capacitively cooled nozzle during the test run as well as the plastic deformation. The consistent deformation is measured on a regular basis using a micrometer screw and approximated by a logarithmic correlation for the evaluation of the test data. The elastic deformation during test cannot be determined directly with the current hardware. A thermo-elastic FEM simulation as performed for prior experiments [11] is aspired for the future. To determine the mass flow rate the measured progressive feed of the piston inside the gel cartridge is converted into the volumetric flow via the piston diameter and then multiplied with the density of the gel. The accurate determination of the gel density is very extensive, since it is expected to be temperature-dependent [12] and density measurements of gels are error-prone due to the non-Newtonian character of the fluids. Nevertheless, some density measurements were performed at ambient temperature using a pycnometer, which yield higher than expected densities for the gelled propellants investigated. These densities were used within the data analysis. However, there is at the moment no accurate temperature density correlation available for the gels used in the tests of interest.

First, the limits of stability and self-contained gel combustion have been investigated. In Figure 6 the obtained combustion chamber pressure is depicted with respect to the propellant mass flux in the chamber. Since up to now only one nozzle with nominal diameter of 6 mm has been deployed, this results in roughly a linear correlation. Out of the total 68 tests only 6 tests have not been stable. Thereof, three prematurely extinctions are addicted to delayed gel injection due to faulty behavior of the hydraulic drive used for the gel propellant feed. With this, the combustion chamber was supposedly insufficiently heated up during the startup phase to support self-contained gel combustion. The other three tests points were performed with “Gel A” and “Gel C”, respectively, and mark with 24.5 bar, 27.2 bar and 25.9 bar the lower limit of the operational envelope. If approaching this limit, also the combustion roughness significantly increases.

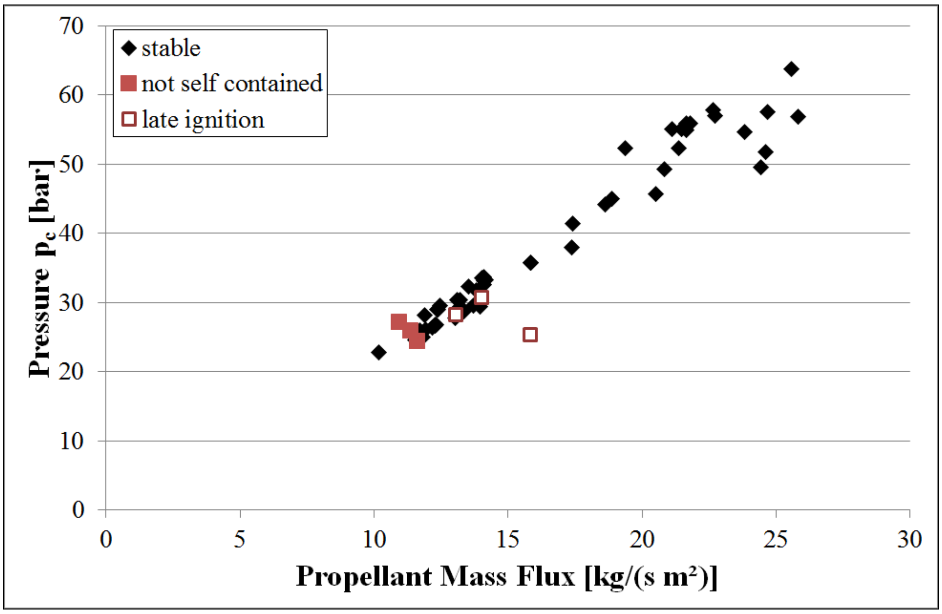

Figure 6: Stability and self-contained combustion

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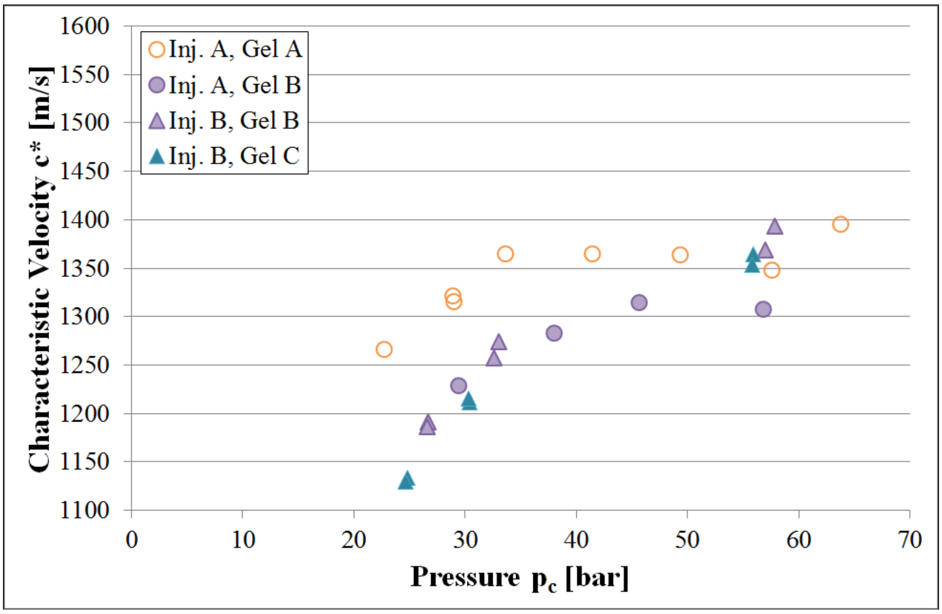

Figure 7: Combustor performance for different gel propellants and two injector elements

For the evaluation and assessment of the combustor performance only load points from tests with a burning time of more than 5 seconds have been considered. The experimental characteristic velocity ${c^*}_{Test}$ is plotted with respect to the combustion chamber pressure p_c in Figure 7. The injector type "A" shows a substantial decrease in performance when approaching the lower operational limit. For moderate pressures an almost constant characteristic velocity exists. Although the small amount of data available creates space for speculations, an optimum mass flow rate/ pressure seems plausible. The figures above 60 bar should be excluded from the discussion in particular since the thermodynamic condition of the injected gelled propellant will change from sub- to transcritical behavior near this point. In comparison, the injector type "B" shows a similar behavior at low combustion pressures but quite likely better performance at higher combustion pressures. Regarding the different gel compositions, the "Gel C" with approximately 25% more admixtures than "Gel B" shows a slightly worse performance. Surprisingly, the "Gel A", which is supposed to have the same composition as "Gel B", provides a significantly higher characteristic velocity and thus also higher performance. Albeit the different treatment of the gelled propellant in the production process as well as storage conditions and aging may have contributed to the different combustion characteristics, other potential causes are a part of the current study. Variations in the propellant composition e.g. lower part of admixtures, differences in the effective density, quality variations of the raw materials as well as human error cannot be eliminated at this time.

3.3 Visual Analyses

First hot fire tests with the sapphire window have been performed using injector "A" and a general purpose industrial zoom camera type DFK Z12GP031 by TheImagingSource. Images taken during these tests are presented in Figure 8. Although such an industrial camera is excellent for monitoring the experiments in the harsh testbed environment, the limited frame rate and image dynamics are drawbacks. No setting could be found where during all phases of operation i.e. igniter operation, startup and nominal operation adequate exposure times could be realized. Furthermore, the specific model used for the tests did not provide a filter ring. Nevertheless, the film recordings could be used for video data analysis of the soot and propellant deposition on the sapphire windows (see Figure 9) and helped to make the decision to continue the testing with injector "B".
A sapphire window dismounted after three consecutive tests with injector "B" is shown in Figure 10. A slight accumulation of soot is apparent but in contrast to tests with injector "A", no deposited propellant was found. The soot merely superficial adheres to the sapphire and can easily be wiped away. So far, no permanent fouling or degradation of the sapphire windows was observed. However, for best results the window has to been cleaned before each test.

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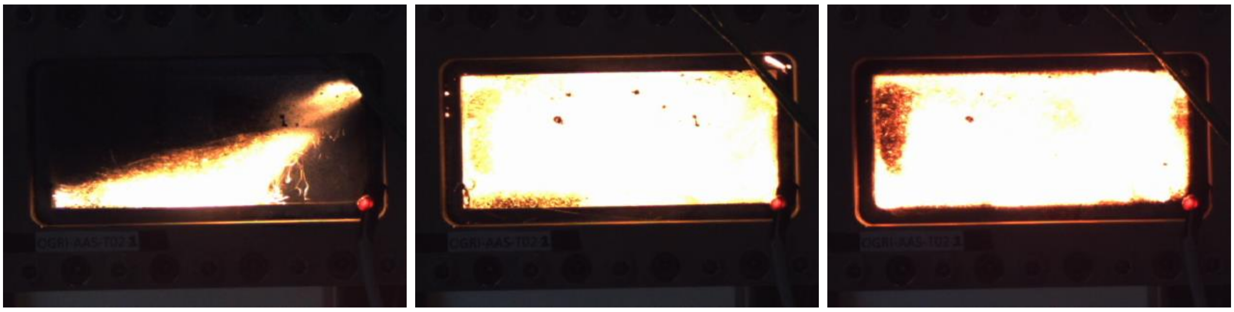

Figure 8: Ignition, startup and nominal operation recorded with general purpose industrial camera
(flow direction from right to left)

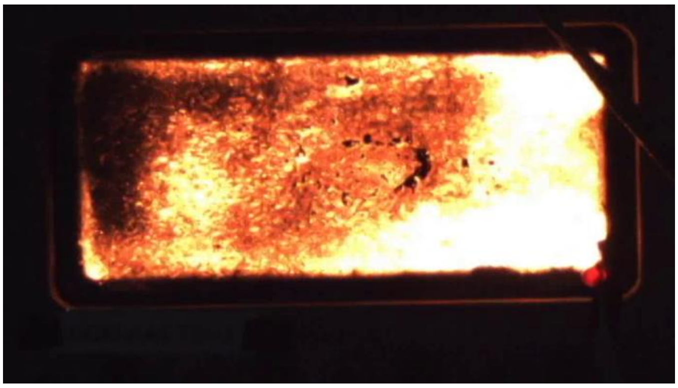

Figure 9: Depositions on sapphire window during test with injector “A” (flow direction from right to left)

Figure 10: Soot on dismounted sapphire window after three consecutive tests with injector “B”
(flow direction from right to left)

Further tests were carried out using a high speed black-and-white camera type FASTCAM SA1.1 by Photron with a 2/ 100 mm ZF fixed focal length objective by Zeiss and CH* filter if appropriate. Snapshots out of the recorded high speed videos from the very first ignition of the gel propellant (boosted with gaseous oxygen) are given in Figure 11. Here, the left hand side represents the unfiltered signal, recorded at 10000 fps, a 768x768 pixel resolution and 1/720000 s exposure time, while the right hand side shows the image from a comparable test using a CH* filter (also 10000 fps, 768x768 pixel, but 1/10000 s exposure time). The two images in the top row are at a nominal combustion pressure of 30 bar. The middle row and bottom row represent the 35 bar and 45 bar case, respectively. The filtered image clearly indicates the zone, where the auxiliary oxygen and the gelled propellant react during the startup phase. However, for the nominal operation, where no supplemental oxygen is injected, no emissions passing the CH* filter could be recorded.
More tests with for example other filter sets are planned for the near future. Also, the correlation of the visual data to the pressure and temperature measurements is foreseen.

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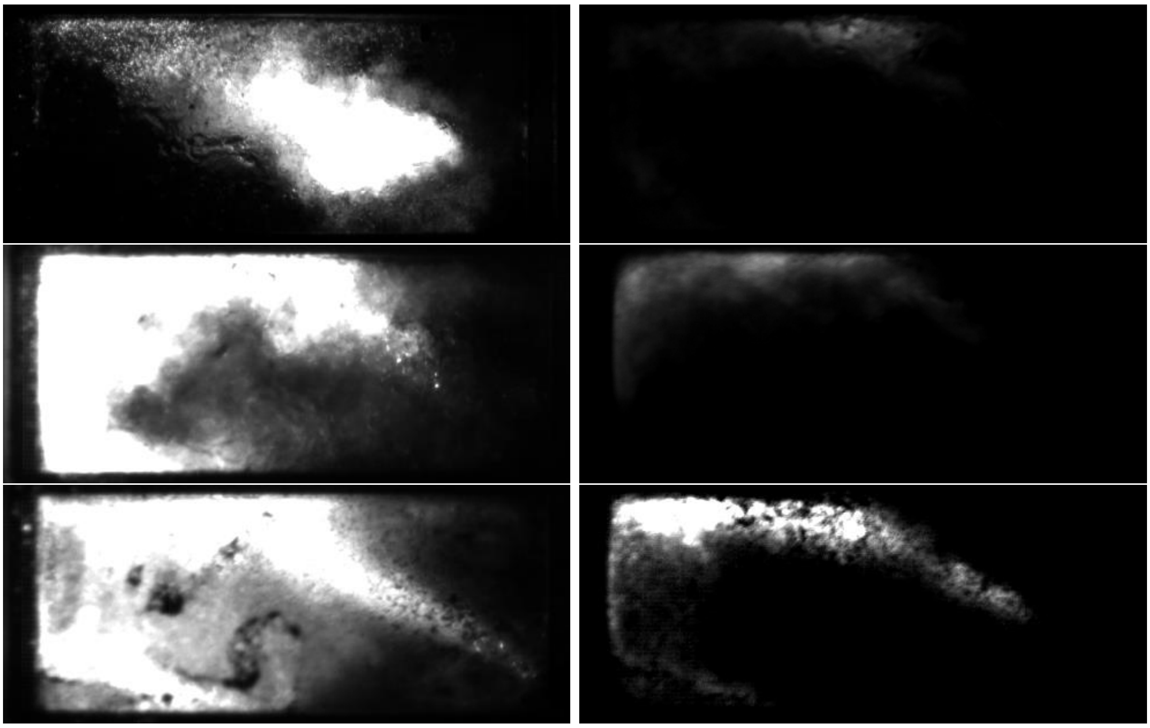

Figure 11: First gel ignition, snapshots from high speed camera recordings, flow direction from right to left (left hand side: unfiltered, 1/720000 s exposure time; right hand side: CH* filter, 1/10000 s exposure time)

4. Conclusion

Gel propellants offer the possibility to realize propulsion systems, which are easy to throttle and which have simple handling and storage characteristics. At the Propellants Department of the Institute of Space Propulsion, German Aerospace Center (DLR), in Lampoldshausen basic research on the development, the rheology, the flow behavior, the spray and the combustion behavior of gel propellants is performed. These investigations are part of the German Gel Propulsion Technology Program (GGPT) and embedded in the Defence & Security Research at DLR.
A new gel model combustion chamber with optical access has been designed, manufactured and deployed. With this chamber, for the first time a detailed analysis and inspection of the chamber processes of a gel rocket motor is possible.
The data of the run-in tests have been evaluated. A stable operation could be verified down to a minimum combustion pressure of approx. 26 bar. The performance of two different injectors and three different monopropellant gels were compared. However, some results are still considered preliminary and have to be verified in the future.
The sapphire windows can withstand the harsh conditions inside the combustion chamber. However, for best results the windows have to be cleaned before each test. Video data of the combustion processes in the combustion chamber were recorded using a general purpose camera as well as a black-and-white high speed camera. The latter provides the more detailed and versatile results. More testing is planned for the near future.

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Nomenclature

Latin

A	[m^2]	Area
$c*$	[m/s]	Characteristic Velocity
d	[m]	Diameter
H	[m]	Height
I_{sp}	[N·s/kg]	Specific Impulse
L	[m]	Length
$L*$	[m]	Characteristic Length
$\dot{m}$	[kg/s]	Mass Flow Rate
p	[Pa]	Pressure
T	[K]	Temperature
W	[m]	Width

Greek

ε_c	[-]	Chamber Contraction Ratio
η	[-]	Efficiency
ρ	[kg/m^3]	Density

Indices

c	Combustion Chamber
t	Throat
test	Experimental
theo	Theoretical

Abbreviations

CC	Combustion Chamber
DLR	Deutsches Zentrum für Luft- und Raumfahrt, German Aerospace Center
GGPT	German Gel Propulsion Technology Program
GRM	Gel Rocket Motor
GRP	Gel Rocket Propellant

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