Overview on Gel Propulsion Activities at DLR Institute of Space Propulsion

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Abstract

Since the year 2000 detailed research and technology pre-development work on gel propulsion for rockets and ramjets is conducted at the DLR Institute for Space Propulsion at Lampoldshausen test site. Test facilities are available to conduct rheological investigations, spray experiments under ambient conditions and combustion tests under ramjet and rocket relevant test conditions. This publication gives a short overview about facilities, instrumentation together with some major results of the work conducted. The presented results cover a rheological law (HBE equation) for the shear viscosity / shear rate dependency, flow behavior, generalized and critical Reynolds number dependencies, spray and combustion behavior in separate experimental setups as well as rocket combustor process investigations in a modular model combustor.

1. Introduction

In the last two decades a growing interest in gelled fuels, propellants or propellant combinations for rocket and ramjet propulsion applications can be observed worldwide. Gelled propellants show safety and performance benefits, which are caused by their non-Newtonian rheological behavior. They are solid at rest, while under a sufficiently high applied shear stress they can be liquefied. Thus the flow of gelled propellants can be varied like that of liquid propellants so that thrust variation of a gel engine can be realized. Together with the potential to be handled simply and safely like solid propellants, gel propulsion systems combine major advantages of the liquid and the solid propulsion systems. Further general information about gel propulsion and information about the status of worldwide activities is given in the overview papers of Natan and Rahimi [1] and Ciezki et al. [2].
Since the year 2000 detailed research and pre-development work on gel propulsion for rockets and ramjets has been conducted at the DLR Institute of Space Propulsion at Lampoldshausen test site. Three test facilities at the M11 test complex [3] are used to conduct spray and combustion investigations relevant for ramjet and rocket propulsion. In the physical/chemical laboratory rheological and other measurements are conducted. A remote controlled production facility is available for the production of gels in propulsion test relevant quantities, if the production process needs a higher safety level. In the present publication an overview about test equipment and main results of the conducted work is given. The DLR Lampoldshausen research and technology development activities are also part of the German Gel Technology Program [2], [4] which was founded in 2001.

2. Definition of gel propellants

According to Dörfler [5] a gel is defined as a transition state between the solid and the liquid state. This means that gels have properties which belong to both states. The dispersed substance and the dispersant penetrate each other and form a coherent system with cavity type structures. The thermodynamic properties, which describe the energy state, are in analogy similar to solids influenced by applied stresses and elongation. The structure of a gel is to a large extent dominated by the geometrical structure and the properties of the dispersed phase.
Due to the fact that this description is to a large extent focused on the state range from rest to low shear rates it does not cover essential aspects of the application in propulsion systems like properties under high shear rates. Thus for propulsion applications the main demands on gel propellants and propellant combinations can be described as:

- Gel propellants or gel fuels and gel oxidizers consist basically of an energetic fluid (dispersant), which has to be gelled, and a gelling agent or gellator (dispersed phase)
- Their shear viscosity values should be high enough under rest and/or they have a high enough yield stress so that sedimentation effects and spill can be avoided
- They can be referred to shear thinning (non-Newtonian) fluids
- Their shear viscosity curves show an upper Newtonian plateau under high applied shear stresses
- Their viscosity values can be reduced under high shear rates to such low values that an effective propellant treatment can be conducted, e.g. atomization (spraying) to sufficiently small droplets

3. Rheology

In order to determine rheological characteristics of non-Newtonian fluids the physical/chemical laboratory is equipped amongst others with two rheometers. For the low up to the intermediate shear rate range a Haake RS1 rotational rheometer and for the high shear rate range a Bohlin RH2000 capillary rheometer were used.
As mentioned above gelled propellants can be described as shear-thinning non-Newtonian fluids. Their shear viscosity η decreases with increasing shear rate up to a constant value at very high shear rates, which is called upper Newtonian plateau. Figure 1 shows in the left diagram the dynamic shear viscosity dependence upon the applied shear rate for a Jet A-1/Thixatrol ST gel as an example. The strong decrease with increasing shear rates can clearly be seen. The upper Newtonian plateau appears at shear rates $\dot{\gamma} > 10^5$ s^{-1} and its viscosity value η_∞ is typically near the viscosity of the Newtonian basic fluid. The location of the upper Newtonian plateau in the η - $\dot{\gamma}$ diagram in relation to the basic fluid depends mainly on the gelling agent, its concentration, the gelling process and amount and type of additives. Further examples are given e.g. in Refs. [6] and [7]. It should be mentioned here that with suitable injectors sufficiently high shear rates and thus sufficiently low viscosity values can be produced so that liquefaction can be realized.

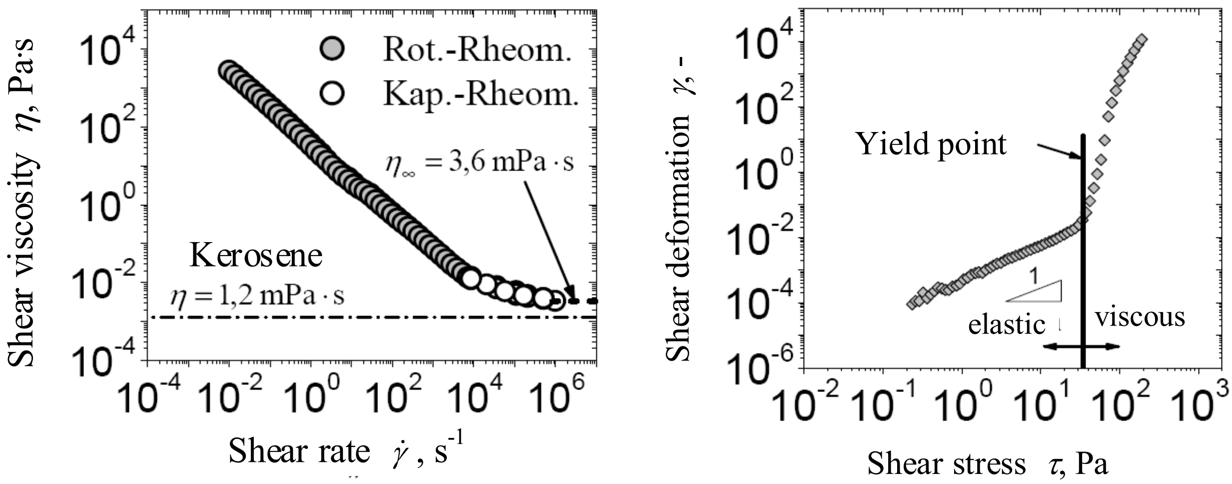

Figure 1: Dynamic shear viscosity η vs. shear rate $\dot{\gamma}$ (left) and determination of the yield stress τ_0 (right) for a JetA-1/ThixatrolST gel. Ref. [8].

Most of the investigated gel propellants show a more or less distinct yield stress[1]. If an applied shear stress is below the material dependent yield stress τ_0, a gel behaves predominantly elastic and only if the applied stress is higher than the yield stress the viscous properties become dominant and the gel starts to flow. The right diagram of Fig. 1 shows the deformation of a typical gel fuel with the transition from elastic to viscous behavior, which has been obtained with the rotational rheometer. It can be seen that at low applied shear stresses the shear deformation is proportional to the shear stress with a gradient of 1 in the log-log diagram. The elastic range is represented by a gradient of 1, where the shear deformation is directly proportional to the applied shear stress, see e.g. Ref. [9]. Thus a gel is elastic under low applied shear stresses as long as its yield stress τ_0 is not exceeded and is viscous with diminishing viscosity as the shear stress is increased in the range above the yield stress.

[1] It should be mentioned that in literature used gel propellants sometimes can be described as clotted fluids without any distinct yield stress. See definition of gel propellants in section 2.

The shear viscosity / shear rate (η / $\dot{\gamma}$) dependence can be described with sufficient accuracy in the whole propulsion relevant shear rate range of eight decades within $10^{-2} < \dot{\gamma} < 10^{6}$ s^{-1} with a satisfying accuracy with an extended version of the Herschel-Bulkley equation (HBE).

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

Shear-thinning fluids have exponents $n < 1$. The HBE equation (1) is based on the in literature often described power law equation $\eta_{PL} = K\dot{\gamma}^{n-1}$. It was yet extended in the past by the yield stress τ_0 to the Herschel-Bulkley equation (HB eq.), but this equation is useful only up to intermediate shear rates. For the extension to the high shear rates, which is necessary for propulsion applications, the HB equation was extended by the constant viscosity value of the upper Newtonian plateau η_∞ and the new equation was called Extended Herschel-Bulkley equation (HBE eq.), see Ref. [10].

Most of the gel propellants show a distinct viscoelastic behavior under small deformation. This arises from its microscopic structure, which is caused for example from very long entangled molecules of several organic gellators. It is described in literature (see e.g. Ref. [9]) that in all structured liquids there is a natural rest condition of the microstructure that represents a minimum-energy state. When the fluid is deformed internal forces act to restore the initial undeformed condition. This means that upon a deformation the liquid stores energy, which is then spent to try to restore the initial condition. Further information is given e.g. in Refs. [9] and [11].

The viscoelastic behavior of a gel under large deformations (also known as non-linear viscoelasticity) is strongly influenced by the nature of the gelling agent. Fluids gelled with crosslinked polymers or silica particles have generally almost no elastic effects under large deformations, due to the fact that the tridimensional structure formed by the gelling agent breaks up under large deformation. On the other hand linear polymers strongly influence the non-linear elasticity, because the linear molecules are stretched under large deformation and generate normal forces inside the fluid. The non-linear viscoelasticity is relevant for aerospace application because, as it is shown in paragraph 5.3 it strongly influences the atomization of gels.

The value of the extensional viscosity is often taken as an indicator of the intensity of non-linear viscoelastic effects. At DLR the extensional viscosity of several classes of fluids was characterized applying the Cogswell theory to the measurements conducted with a capillary rheometer [12]. An example of the results obtained is shown in Figure 2. The two investigated linear polymer solutions, EG1 and LP3, have values of the extensional viscosity much larger than those of the crosslinked polymer solution CP1 and of the silica suspension EG2.

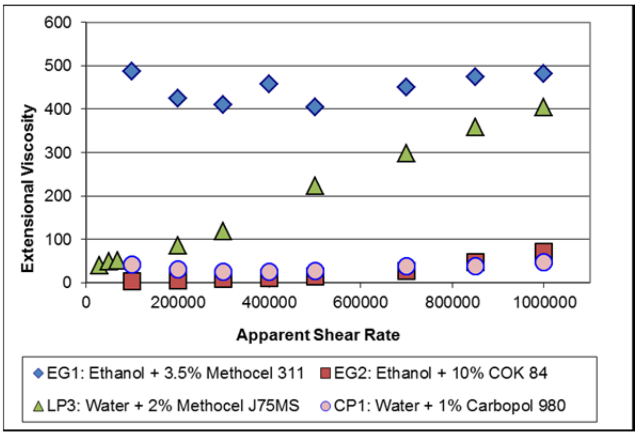

Figure 2: Extensional viscosity values for four fluids with distinct yield stress (gels). From Ref. [13].

4. Flow behavior

Comparing the velocity profiles of flows of Newtonian fluids and of shear-thinning gels through circular tubes of constant diameter under laminar, fully developed and steady state conditions it can be seen that shear-thinning flows show broader profiles in comparison to Newtonian fluids with steeper velocity gradients near the wall and lower center line velocities. Numerically calculated velocity profiles of four typical gels are presented as examples in the two diagrams of Figure 3. Also it can be seen in these diagrams that the yield stress leads to an unsheared plug flow in the core region of tube flows, because here the occurring stresses are below the yield stress. Increasing average velocities and thus increasing wall shear stresses lead to smaller plug flow regions by decreasing the stress ratio

τ_0/τ_w which marks the border of the plug region on the dimensionless tube radius r/R. More detailed information is given in Refs. [6], [7] and [10]. It should be mentioned in this context that for power-law and Herschel-Bulkley fluids analytically determined velocity profiles have been derived, see Ref. [14]. For HBE fluids, however, an analytical solution could be found by Madlener et al only for fluids with an exponent n = 0.5 [15].

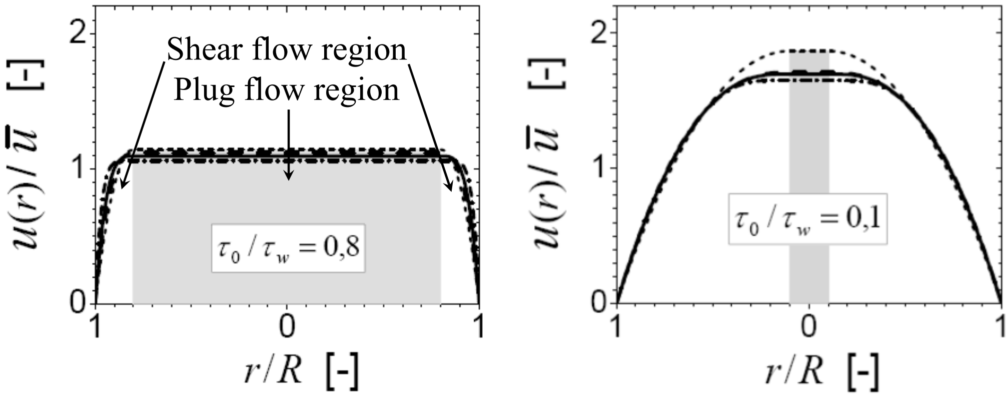

Figure 3: Dimensionless laminar velocity profiles in tubes for the 4 gel test fuels at 3 different τ_0/τ_w. The different lines present the velocity profiles of four different gels, whose data are presented in Ref. [6].
Left: Velocity profiles for τ_0/τ_w = 0.8; Right: Velocity profiles for τ_0/τ_w = 0.1

Dimensionless numbers like Reynolds, Weber and Ohnesorge number are typically used for the characterization of flow and spray behavior of Newtonian fluids. For non-Newtonian fluids like gels the knowledge about characteristic numbers is quite low up to now. The Reynolds number, which can be interpreted as as the ratio of the inertial forces to the viscous forces and which is written for Newtonian fluids as $Re_{NF} = \rho\, \bar{u} \cdot L / \eta$ (ρ density, $\bar{u}$ average flow velocity, L characteristic length, η dynamic shear viscosity), cannot be used for gel flows due to the fact that the viscosity is not constant. Based on the HBE equation Madlener et al could derive analytically a generalized Reynolds number [16].

$$Re_{gen\,HBE} = \frac{\rho \cdot \bar{u}^{2-n} \cdot D^n}{\frac{\tau_0}{8}\left(\frac{D}{\bar{u}}\right)^n + K\left(\frac{3m+1}{4m}\right)^n 8^{n-1} + \eta_\infty \frac{3m+1}{4m}\left(\frac{D}{\bar{u}}\right)^{n-1}}$$

$$with \quad m = \frac{n \cdot K\left(\frac{8\bar{u}}{D}\right)^n + \eta_\infty\left(\frac{8\bar{u}}{D}\right)}{\tau_0 + K\left(\frac{8\bar{u}}{D}\right)^n + \eta_\infty\left(\frac{8\bar{u}}{D}\right)} \qquad \textbf{(2)}$$

Furthermore the characteristics of the critical HBE Reynolds number Re_{crit}, which give information about the transition from laminar to turbulent flow conditions, could numerically be determined for tube flows based on the method introduced by Ryan and Johnson (for details see Refs. [6], [7]). Figure 4 presents the critical Darcy friction factor f_c in dependence upon the exponent n of the power law term in the HBE equation. The critical Darcy friction factor is related to the critical HBE Reynolds number by $f_c = 64/Re_{crit}$. The full lines in the diagram present the numerically determined friction factor curves for different yield stresses. These three curves fit quite well in the region $0.7 < n \leq 1.0$ with theoretical models from literature (R+J, Trinh, Mishra), which are listed in Ref. [6], and separate from them at lower n.
Going from n = 1 (Newtonian case) to lower exponents n it can be seen that both the shear-thinning and the yield stress lead to a stabilization of the laminar flow, which shifts the transition to higher Reynolds numbers and thus lower critical Darcy friction factors. A minimum of f_c (and thus a maximum for Re_{crit}) exists at approximately $n \approx 0.6$ for all presented curves. Below $n \approx 0.6$ the f_c values increase again and also the presented curves separate. This means that at low n not only a single curve represents the critical friction factor and therewith the critical Re_{crit} dependence from n. Further information is given in Refs. [6].

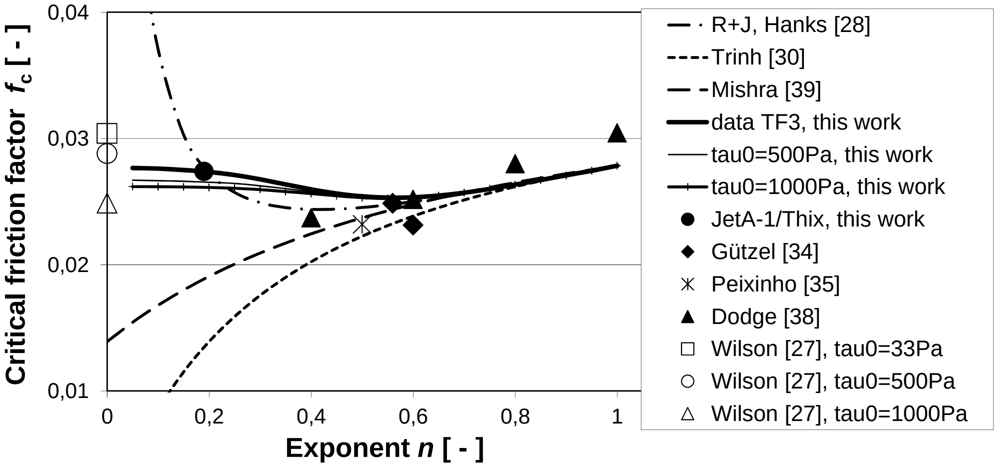

Figure 4: Critical Darcy friction factor f_c in dependence upon the HBE exponent n. Comparison of theoretical approaches and experimental results. For cited literature in this diagram please see Ref. [6].

5. Spray behavior

5.1 Experimental setup

The experimental setup for the spray investigations consists of a cartridge with the fluid to be investigated, a hydraulic driving unit and a modular injector unit. For the visualization of the spray patterns the shadowgraph-technique was used, implemented with two CCD cameras, one parallel and one perpendicular to the plane of the injectors, and two Nanolite spark lights as light sources. Droplet size measurements of the spray were conducted with a Malvern Spraytech, based on laser diffraction. A schematic representation of the setup is given in Figure 5.

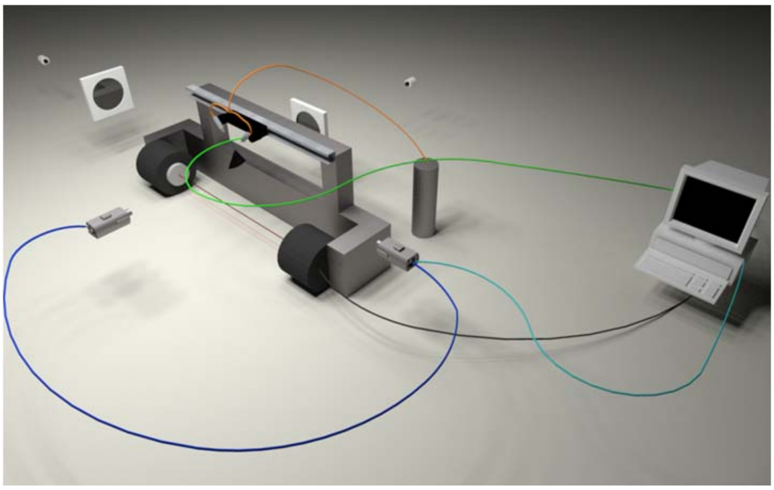

Figure 5: Spray tests experimental setup.

5.2 Influence Al loading

The addition of metal particles like aluminum or boron to gel propellants is of special interest due to their significantly higher energy content per unit volume in comparison to the pure hydrocarbon fuels. Slurry fuels, where metal particles are added to liquid hydrocarbon fuels, showed several severe problems in connection with stability and sedimentation effects. In gelled fuels with metal particle addition, however, particle sedimentation effects are significantly lower than in slurries and separation effects occur only at very high acceleration levels.

For example, the influence of different aluminum loadings on the atomization behavior was studied in Ref. [17]. The tests were conducted with a Jet A-1 based gel, gelled with 7.5 wt.-% Thixatrol ST and 7.5 wt.-% Miak. Four different aluminium loadings were tested, from 10 wt.-% to 40 wt.-%. The tests were conducted with aluminium particles type MEP027 from Ecka Granules, with a nominal diameter of 1.5 µm and a measured D_{50} of 1.22 µm. The investigations were conducted with a like-on-like impinging jet injector with nozzles (orifices) with a diameter D = 0.7 mm and an impingement angle 2θ = 90°.

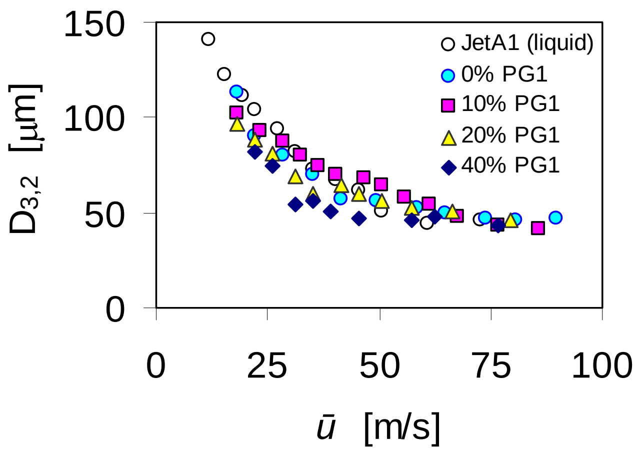

Figure 6: Average droplet diameter $D_{3,2}$ as a function of injection speed for 5 fluids with different Al particle loadings. From Ref. [17].

The results are shown in Figure 6, where for comparison also the averaged droplet diameters $D_{3,2}$ of the liquid kerosene are included in the graph. It can be seen for all investigated fluids that with increasing injector exit velocities $\bar{u}$ decreasing Sauter diameter $D_{3,2}$ occur, whereas the slope flattens for higher $\bar{u}$. At higher $\bar{u}$ a lower limit at about $D_{3,2} \approx 45$ µm seems to exist for all investigated fuels. The gel with 40 wt.-% aluminium shows a stronger irregularity, which seems to be caused by the higher Al loading of the gel.

5.3 Thread formation

During several spray tests conducted at DLR (for example [7]) it was observed that some gels did not lead to the formation of droplets. Instead, thread-like structures were formed, as shown in Figure 7. These structures have a significantly lower surface contact area with the surrounding atmosphere when compared to droplets and thus could lead to a decrease in combustion efficiency and the accumulation of unburned material at the wall of the combustion chamber.

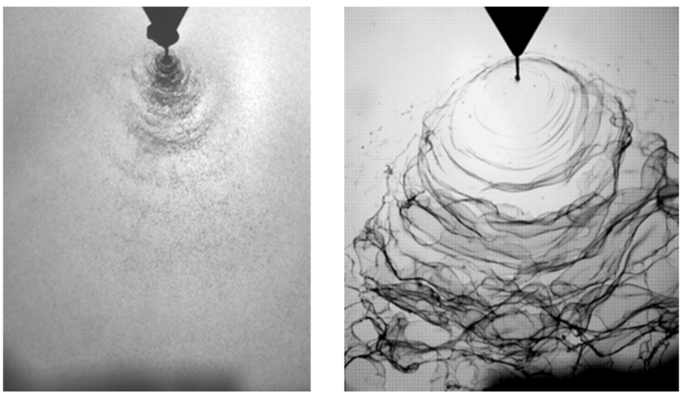

Figure 7: Comparison of droplets and threads formation.
Left: Ethanol + 10% COK 84. $\bar{u}$ = 45.5 m/s. Right: Water + 3.1 % Methocel J12MS. $\bar{u}$ = 46.8 m/s.

An experimental investigation was conducted to determine which physical properties influence thread formation and to understand the mechanism leading to the creation of these structures. The results are presented in Refs. [12] and [18].

In the first part of the campaign, several classes of non-Newtonian fluids were tested, in order to isolate the factors leading to thread formation. In particular the influence of shear viscosity, surface tension, yield stress and elongational viscosity on the formation of threads was studied. The second part of the campaign was focused on

Boger fluids, a class of fluid that allows the separation of viscous and elastic effects. In order to obtain quantitative results from shadowgraph images, a code was implemented that allows the determination of a characteristic dimension of the threads.
Based on the research conducted, it is concluded that thread formation is caused by nonlinear viscoelastic effects. The viscoelasticity of the fluids tested was characterized through elongational viscosity measurements. Fluids with large values of elongational viscosity produced threads. The intensity of viscoelastic effects for Boger fluids was associated to the relaxation time. A clear correlation between the relaxation time and the dimension of the threads obtained was observed.
A two-step physical mechanism is proposed to explain the formation of threads in an impinging jet injector. The first step of the model is the break-up of the liquid sheet in transversal ligaments due to aerodynamic instability. This first step can also be observed when droplets are formed. In opposition, the second step controls the formation of droplets or threads. When droplets are produced the ligaments breakup due to capillary instability. On the other hand, when the level of elasticity is high enough, the transversal ligaments become more stable and do not disrupt into droplets, rather they stretch and fold forming the structures called threads in the present work.

6. Gel fuel combustion under ramjet relevant conditions

6.1 Experimental setup

The combustion behavior of gelled fuels at conditions relevant for ramjet application concerning pressure and air inlet temperature was investigated with a pressurized combustion chamber, as shown in Figure 8. The chamber was designed to reach a maximum combustor pressures of 12 bar and maximum air inlet temperatures of 800 K. The chamber had a diameter of 0.3 m, a height of 0.9 m and consisted of steel rings, which were hold together by a hydraulic clamping device. The upper steel ring contained quartz windows to provide optical access to the chamber. An hydrogen/oxygen (H_2/O_2) burner was used to ignite the gel spray. In the lowest chamber ring three exit nozzles were mounted. The nozzles could be changed in order to vary the throat area of the chamber nozzles. The air entering the combustion chamber was heated by H_2/O_2 burners in a separate set-up (vitiated air).
The investigations were conducted with a like-on-like impinging jet injector with nozzles of diameter D = 0.7 mm and an impingement angle $2\theta = 90°$. Experiments were conducted at 6 and 11 bar with three different temperatures of the incoming air: 300, 550 and 800 K. The gel jet exit velocity $\bar{u}$ was varied in four steps between 30 m/s and 60 m/s.

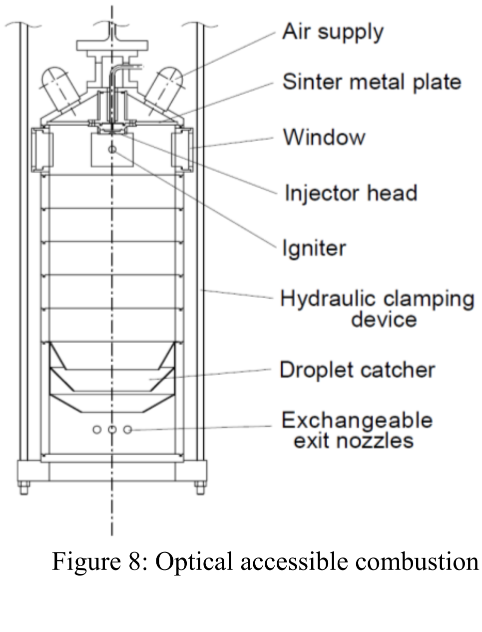

Figure 8: Optical accessible combustion chamber used to conduct tests under ramjet relevant conditions.

6.2 Influence of Aluminum content on the combustion

The influence of different aluminum loadings was studied in Ref. [17]. The tests were conducted with a Jet A-1 based gel, gelled with 7.5 wt.-% Thixatrol ST and 7.5 wt.-% Miak. Four different aluminum loadings where tested, from 10 % to 40 %. The spray behavior of this gel was also characterized, as described in paragraph 5.2. As a criterion for the quality of combustion, a combustion efficiency $\bar{\varepsilon}$ defined as the ratio of the real to the ideal difference between the outgoing and incoming heat fluxes was calculated. Heat losses through the combustion chamber wall were not considered.

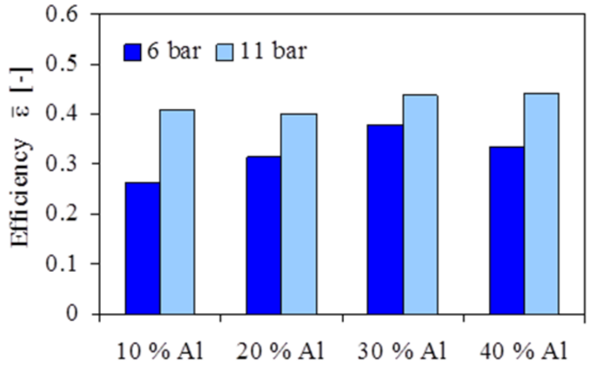

Figure 9: Average efficiencies $\bar{\varepsilon}$ of the gels with four different particle loadings at the two different pressure levels. From Ref. [17].

As a summary of the combustion characteristic, Figure 9 shows the calculated efficiency for the different pressure levels and particle loadings as an average of all conducted mass flow rates. At the low pressure level the average efficiency of the combustion reaches a maximum for the gel containing 30 wt.-% of aluminum. At the higher pressure level of 11 bar this characteristic was obtained less pronounced.

6.3 Influence of Nano-Al on the combustion

The increased reactivity of nano-particles makes them attractive for substituting micro-sized aluminum in gel propellants in order to increase combustion efficiency. Significant increases in propellant burning rates, shorter ignition delays and shorter agglomerates burning times were recently observed for composite solid propellant formulations containing Al nano-particles. Combustion tests have been conducted under ramjet relevant conditions with the following gels:

- Jet A-1 + 7.5% Thixatrol + 30% MEP027 (micro-Al)
- Jet A-1 + 7.5% Thixatrol + 15% MEP027 (micro-Al) + 15% Alex (nano-Al)
- Jet A-1 + 7.5% Thixatrol + 30% Alex (nano-Al)

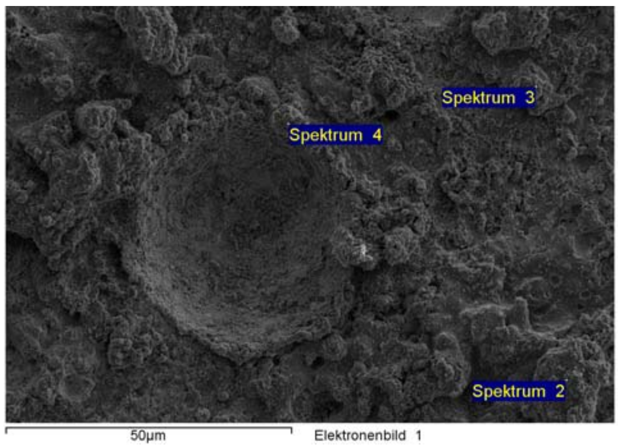

Figure 10: SEM image of the combustion products collected with a rapid insertion probe in the plume of the combustor. The combustion products have a "coralline" aggregate structure.

The tests conducted revealed that both the thermal and the c^* efficiency are slightly lower for the combustion of gel containing Alex particles compared to the combustion of gel containing micro-sized aluminum.
Two rapid insertion probes were used to collect the combustion products from the combustion chamber plume. The first probe developed was a water cooled, rapid insertion probe made of copper. It allowed the collection of an

amount of condensed combustion products sufficient for a wet chemical analysis. The amount of oxidized aluminum in the combustion products was very low for all the test conducted, ranging from 30 % to 50 %. The gel containing nano-Al exhibits a slightly lower oxidation than the gel with micro-Al.
The other probe was developed to collect combustion products to analyze with a Scanning Electronic Microscope (SEM). To determine the superficial chemical composition of the sample X-Ray Photoelectron Spectroscopy (XPS) technique was used. SEM and XPS were made available at the DLR Institute of Structures and Design. From these observations, it was concluded that the main combustion products were aggregates with a diameter in the 20 - 200 µm range and with a "coralline" structure. The oxidation of the aluminum in the aggregates was very limited. The aggregates did not show signs of local melting: single Alex particles could be still distinguished on the surface.
The high reactivity of Alex is caused by the nanostructure of these particles. But the particles aggregate reducing the effective specific surface area of the nano-particles. Therefore the combustion efficiency is probably influenced more by the size of the aggregates and not by the size of the single aluminum particles. This may explain why the use of Alex does not lead to the expected increase in efficiency under the conditions of the tests conducted.

6.4 Influence of high vapor pressure species

The motivation for the investigation on high vapor pressure species (HVPS), Ref. [19], was to increase the burning rates of gel fuel droplets. The high-vapor-pressure species are more volatile due to the relatively low boiling point temperature, meaning the equilibrium vapor pressure is an indication of a liquid evaporation rate. Most of burning process occurs within the gas phase, therefore if the substance evaporates faster theoretically, combustion is enhanced. The following HVPS where added to a Jet A-1 + 7.5 % ThixatrolST gel:

- Jet A-1 + 7.5% Thixatrol + 15% hexane
- Jet A-1 + 7.5% Thixatrol + 30% hexane
- Jet A-1 + 7.5% Thixatrol + 30% cyclohexane
- Jet A-1 + 7.5% Thixatrol + 30% hexane + 30% Al
- Jet A-1 + 7.5% Thixatrol + 30% hexane + 30% Mg

In general, the comparison of experimentally obtained results indicates that the addition of the volatile compounds has only a minor effect on the atomization and combustion.

7. Gel as rocket propellant

At DLR Institute of Space Propulsion a modular rocket test facility (TD-B) was developed and built, with which the development of gel combustor processes under rocket relevant conditions can be conducted.

7.1 Experimental setup and materials tested

Two images of the experimental setup with the model combustion chamber (called technology demonstrator TD-B), which is used to conduct tests with gelled propellants under rocket relevant conditions, are shown in Figure 11. The capacitive cooled combustion chamber is cylindrical with an internal diameter of 50 mm and is made of stainless steel. The length of the combustion chamber was varied between 200 and 400 mm and exit nozzles of a broad range of diameters were used.

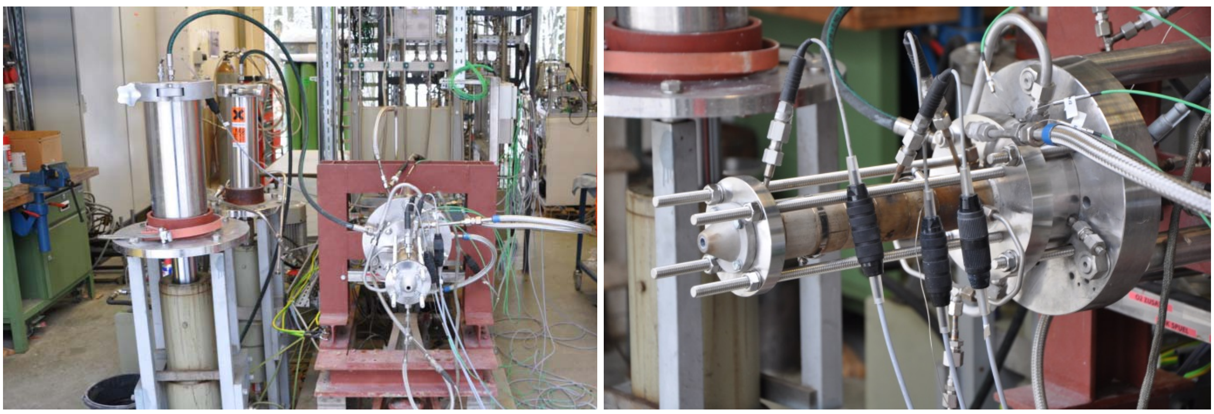

Figure 11: Model combustion chamber used for gelled propellants (TD-B).

The chamber was designed for a maximum pressure of 100 bar. The injector is modular, so that different injector configurations can be tested. The ignition of non-hypergolic propellants is obtained with a H_2/O_2 igniter. The gel propellants were stored in cartridges with a movable piston inside. With hydraulic driving units the gel propellants can be fed to the injector head by moving the piston and pushing the gel into the connection tubes.
Tests were conducted with two gel monopropellants (GP1 and GP2). Both gels are based on the same liquid monopropellant. GP1 was gelled with Aerosil, a kind of fumed silica produced by Evonik. The composition of GP2 was developed by Fraunhofer ICT, to avoid the use of Aerosil.

7.2 Combustion stability and throttleability

A test campaign was conducted in order to determine under which conditions the gel propellants GP1 assures a stable combustion. It was found that this gel gives a stable combustion only above a critical pressure level. The critical value of the pressure increased with increasing the mass flow rate. An example of the results obtained is shown in Figure 12.

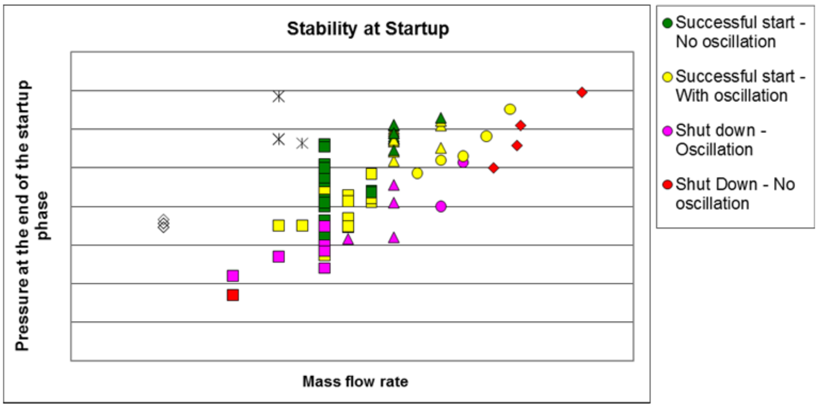

Figure 12: Stability at startup as function of the mass flow rate and of the pressure reached at the end of the ignition phase when the igniter and the additional oxygen are turned off. The different symbols correspond to different exit nozzle diameters.

Tests were conducted to determine the possibility to throttle an engine with the GP1 propellants. The tests showed that the engine could be easily throttled, as long as the pressure in the combustion chamber remained above the critical pressure. An example of the pressure and thrust traces obtained during one of this tests is given in Figure 13.

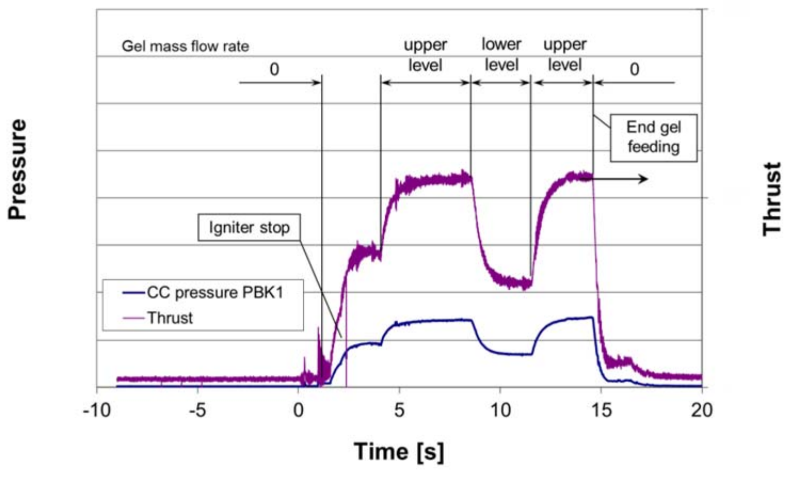

Figure 13: Combustion test with gel GP1: pressure and thrust traces. The test shows that the engine can be throttled.

7.3 Comparison of the combustion of two different gel monopropellants

Recently tests were conducted to compare the combustion of GP1 and GP2 gel propellants. It was found that the critical pressure for the gel GP2 was much lower than the one of the gel GP1. When using the gel GP2 it was possible to throttle the engine in a larger range of combustion chamber pressure and thrust levels.
Another strong limitation of the gel GP1 is related to the use of Aerosil as gelling agent. Aerosil did not gasify during the combustion and had a tendency to accumulate at the combustion chamber walls. On the other hand, GP2 shows not this strong tendency to accumulate on the wall and did not lead to problems like e.g. to the blockage of orifices to the pressure transducers. This offers more detailed analysis of the experiments as for example spectral analysis methods.

8. Conclusion

Gel propulsion systems combine major advantages of solid and liquid propulsion systems. The research and technology pre-development activities on gel propulsion at the DLR Institute of Space Propulsion were started in the year 2000. A good understanding of various aspects of the rheology, flow behavior, spray behavior and combustion characteristics of gel propellants could be obtained up to now.
Summarizing it can be said that in combination with the results and technology development activities obtained within the German Gel Technology program the developed gel propulsion technology seems to be ready for first applications. Nevertheless there are still numerous scientific questions to answer and further technology development tasks have to be solved so that the technology can be adapted to further applications in the aerospace and space sector.

9. Acknowledgment

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10. Nomenclature

c^*	efficiency, -
D	tube diameter of injector orifice diameter, m
$D_{3,2}$	Average droplet diameter (Sauter mean), m
f	friction factor, -
K	pre-exponential factor in HBE eq., $Pa \cdot s^n$
n	exponential factor in HBE equation, -
r	radial coordinate, m
R	tube radius, m
Re_{gen}	generalized Reynolds number, -
$\bar{u}$	average velocity, m/s

Greek

γ	shear deformation, -
$\dot{\gamma}$	shear rate, s^{-1}
$\dot{\varepsilon}$	elongational viscosity, s^{-1}
η	shear viscosity, Pa·s
η_∞	shear viscosity of upper Newtonian plateau, Pa·s
η_E	elongational viscosity, Pa·s
τ	shear stress, Pa
τ_0	yield stress, Pa
τ_w	wall shear stress, Pa
θ	impingement half angle, -

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