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STATUS OF GEL PROPULSION IN THE YEAR 2010 WITH A SPECIAL VIEW ON THE GERMAN ACTIVITIES

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Summary

Gel propellants are interesting candidates for rocket and ramjet propulsion systems. Due to their non-Newtonian flow behavior they offer the possibility to built throttleable engines with easy handling and storage capabilities. The current publication gives a very short description of the actual state of knowledge and technology development whereas a special focus will be given on the activities within the scope of the German Gel Technology Program. Furthermore a short overview about some existing and new proposals for applications of gel propulsion systems is given. Summarizing it can be said that up to now the understanding of basic processes as well as the knowledge about combustor and engine technology on gel propulsion has significantly improved, but there are still open gaps to close.

1. INTRODUCTION

In the last decades gel fuels and propellants received increasing interest for applications in rocket and ramjet propulsion systems, because of their safety and performance benefits. Gelled propellants behave as non-Newtonian shear-thinning fluids, which are solid at rest and which can be liquefied if high shear rates are applied. Due to this unique flow behavior they offer the possibility to develop engines, which can both be throttled similar to engines with liquid propellants and which have simple handling and storage characteristics similar to engines with solid propellants.

Since ca. the 60`s of the last century work on solid loaded fuels like slurries and gels was conducted in the USA. Within the scope of this early work on gel propulsion the investigations at US Air Force and US Navy were focused mainly on propellant combinations with hydrazine based gels. After a decline in the mid of the 70´s of the last century the interest in gels increased again in the 80´s due to new demands on the performance of future propulsion systems like thrust and energy management, insensitive munitions (IM) criteria, fuels with high energy density, low toxicity, improved handling and storage safety, low over-all life costs, etc. At the end of the 80´s and the 90´s work on gel propulsion started also in several other countries. More detailed information about the history and the status up to the year 2000 is given in the overview report of Natan and Rahimi [1].

Significant progress has been made in the last years in basic research as well as in work on propulsion system development and demonstration. This can be seen on the one hand in the increasing number of publications and in the conduction of whole sessions about gel propulsion at several international conferences in the last years. These conferences were mainly EUCASS2007, EUCASS2009, 38th Int. Annual Conference of ICT 2007, German Aerospace Congress 2008 and the AIAA Joint Propulsion Conferences in 2009 and 2010. On the other hand the engine process technology development is meanwhile so much advanced in distinct countries that flight demonstration tests with gel propulsion systems were conducted successfully in USA [2],[3] in 1999 and 2000 and in Germany in 2009. The German flight demonstrator activities will shortly be described in the present publication in chapter 5.

Summarizing it can be said that up to now the understanding of basic as well as of technology relevant processes of gel propulsion has significantly been increased. The basic process relevant areas are mainly related to rheology and the flow, spray and combustion behavior of gelled energetic fluids. The technology relevant areas cover mainly combustor process control and engine development. Nevertheless there are still open gaps to close.

The present publication will give a very short overview about the state of the art in various relevant areas of research and technology development on gel propulsion, which is available in the open literature, whereas the activities in the scope of the German Gel Technology Program [4],[5] will be updated in more detail. The main

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focus of this publication is on earth storable gels and thus cryogenic gels will not be discussed in detail. Open gaps of research and development will also be addressed here and some proposals for possible applications will be presented. It should be mentioned that this publication makes no claim to be complete. It shows only some important findings, facets and developments for the way forward to future gel propulsion systems.

2. SYSTEM RELEVANT ASPECTS OF GEL PROPULSION

As mentioned above, a gel rocket motor (GRM) combines major advantages of a solid rocket motor (SRM) and a liquid rocket motor (LRM). Also for airbreathing ramjets the application of gel fuels is advantageous because of higher safety aspects in comparison to liquid fuels.

Gelled propellants behave in the tank at rest like solids. Under sufficiently high applied shear forces, however, they can be fed through pipes due to their shear-thinning behavior. They can be liquefied to a large extent upon injection into the combustion chamber by the very high shear rates acting on the flow through suitable injectors. More detailed information about their rheological, flow and spray behavior will be given in the subsequent chapters 3 and 4.

Figure 1. Examples of gelled fuels

Common features of all kinds of gel rocket motors are:
– controllable thrust, either by throttling or by intermittent operation
– low plume signature if no or only very small amounts of solid metal fuel or inert particles are added
– capability to increase the energy content of the propellants by adding e.g. metal particles without the tendency that the particles form sediments in the tank
– avoiding of fuel slosh in tanks, which can be a problem for LRMs. This is caused by the used tank design and the fact that the gel propellants are solid at rest.

Within the scope of the German Gel Technology Program, it could be shown that the biggest advantage of a GRM is, if suitable ingredients for the propellant gels are used, the potential to combine
– a superior degree of insensitivity
– easy handling, transport and storage regulations and methods
– environmental friendliness of propellant and exhaust gas

For a reliable analysis of the capabilities of GRMs it has to be mentioned that there are some shortcomings. Comparing a GRM to a solid rocket motor (SRM) it has to be mentioned that
– the lower density of a non-metallized propellant requires up to now a larger volume of the tank
– more components are needed (tank, pressurization, gel flow control device and combustion chamber)
– a lower maximum thrust density exists

Comparing a GRM to a liquid rocket motor (LRM) it has to be mentioned that
– lower specific impulses exist in comparison to cryogenic LOX (LCH4/LO_2, kerosene/ LO_2, LH_2/LO_2, etc.) engines. (if the work of Palaszewski et al on gelled hydrogen is not taken into account, see e.g. [6])
– higher feeding pressures are necessary if the viscosity of the gels is not significantly decreased before entering the feeding lines to the engines

3. CHEMICAL COMPOUNDS AND GEL PRODUCTION

There exists currently no generally accepted definition of a gel. From a chemical point of view IUPAC Gold Book defines a gel as: "*Non-fluid colloidal network or polymer network that is expanded throughout its whole volume by a fluid"* [7]. From a rheological point of view a gel can be described as a viscoelastic shear-thinning fluid and its storage modulus should commonly be higher than its loss modulus if it is exposed to oscillatory conditions. Its shear-thinning behavior will be described in the subsequent chapter in detail and for further information see e.g. Ref. [8]. From an application point of view with respect to rocket and ramjet propulsion, it is obvious that a gelled propellant should behave under storage conditions similar to a solid and when applied to a shear stress (caused e.g. by the applied feeding pressure) similar to a liquid.

For the production of a gel a liquid (as the continuous phase) is compounded with a gelling agent (as the disperse phase). In case of organic gellants the production of the gels is in many cases very easy, because the gellants can be applied to the liquid by simple stirring. For dispersed systems a good dispersion and deagglomeration of the solid particles is required. This can be achieved for example with special dissolver mixing devices, by ultrasonic treatment or by resonant acoustic mixing. In most cases additives are necessary for preventing agglomeration and to achieve stable gels.

For rocket propulsion applications some typical basic liquid fuels and oxidizers, which were gelled and presented in literature, are listed here. Liquid oxidizers are for example nitric acid also enriched with nitrogen oxides (RFNA, IRFNA), hydrogen peroxide (HTP), dinitrogen tetroxide (NTO), aqueous solutions of ammonium dinitramide (ADN) or ammonium nitrate (AN), etc. Liquid fuels are for example hydrazine and its derivatives (MMH, UDMH), paraffin oil, kerosene, RP-1, nitromethane (NM), ethanol, polymers with low molecular mass (e.g. HTPB), etc., see e.g. Refs. [9]-[14]. To increase the specific impulse organic fuels often are blended with metal particles like aluminium, boron or magnesium, see e.g. Refs. [15]-[18]. This addition is useful with gels, because a sufficient yield stress hinders the sedimentation under storage conditions. For slurry fuels, however, sedimentation cannot completely be avoided.

Gelling agents are typically organic materials like cellulose derivatives, pectin, starch, agar, gelatine, etc. or inorganic particles mainly in sub-micron size like fumed silica (Aerosil, Cabosil, etc.), nano-particles of aluminium (ALEX), carbon nanotubes (CNT), etc., see e.g. Refs. [6],[19]-[21].

In the following some relevant investigations are described as examples. The majority of published work on gel propellants and propulsion is focused on bipropellants, where the safety aspect due to the spatial separation of the gels is obvious. In this field hypergolic combinations were often investigated, because they offer an instantaneous ignition and the use of igniters can be avoided. Especially under these conditions gelled components are distinguished when e.g. a projectile or fragments penetrate the walls of the storage tanks resulting in a locally limited direct contact of the reactants due to the immobility of gelled fuels in static conditions that prevent the mixing of the two components [22]. The most prominent example of a gelled hypergolic bipropellant combination is hydrazine or its derivative MMH together with RFNA, see e.g. Refs. [23]-[25]. This combination was also used in the above mentioned flight demonstrator missile of TRW [2],[3],[26]. For more detailed information of work conducted up to the year 2000 a comprehensive list of used oxidizer/fuel combinations is provided in the overview report of Nathan [1].

Within the scope of newer work Winborg et al suggested recently a new gelled oxidizer based on a solution of ADN in water [9],[10], which is much easier to handle than nitric oxide (RFNA, etc.) based gels and could thus be of interest.

Recently gelled monopropellants with sufficient insensitive properties win an increasing interest. This shall lead to a simpler missile design and less-weight structures. E.g. nitromethane/hydrogen peroxide mixtures gelled with fumed silica were investigated and characterized as high energetic and featuring an attractive burning behavior. Unfortunately within these investigations an insufficient stability and insensitivity was found [27],[28].

Nitromethane (NM), which is a classical liquid monopropellant [29], was proposed to be used for gelled propellants [30]. Unfortunately it has to be mentioned that NM features only limited performance data. To increase the performance of nitromethane Weiser proposed to add up to 15% aluminium [31]. The investigated samples were gelled with fumed silica and included micro-sized Alcan and ultrafine ALEX. The experiments resulted in increased flame temperatures in agreement with thermodynamic calculations confirming a higher specific impulse.

Sabourin et al. [32] extended this work showing that NM may be gelled solely by passivated nano-Al particles. A more recent study demonstrates that also other metal particles (boron, magnesium, silicon, titan, zirconium) and metal hydrides (AlH_3, MgH_2) are able to increase at least the volume specific impulse of NM [16]. The same study indicated that fumed silica may interact exothermically with metals like aluminium or magnesium within a thermite type reaction. The increase of performance by metal particles is mainly generated by the exothermic oxidation with water to metal oxide and hydrogen with low molecular mass. So Ivanov investigated successfully mixtures of water and ultrafine aluminium particles gelled with 3% polyacrylamide, see Refs. [33],[34]. A review of further investigations of gelled propellants including nano-particles is included in the publication of Yetter [15].

Recently it was demonstrated that nearly pure hydrogen peroxide (>99%) can compatibly be gelled with polyvinyl-pyrrolidon (PVP) that concurrently act as a fuel [35]. For 20% PVP a gelled monopropellant with a vacuum specific impulse of 2700 Ns/kg results with reasonable sensitivity according to shock and friction, acceptable gel rheology and very fast burning behavior in a pressure range from 0.2 to 13 MPa.

Ionic liquids are receiving an ever-increasing interest due to their unique properties. They consist entirely out of ions and show good thermal stability, electric conductivity and extremely low vapor pressure. Due to the very low vapor pressure a significantly reduced environmental risk and better storage and handling properties are expected combined with higher performance. They also enable an increased operation temperature range compared to conventional monopropellants. This makes them also attractive as potential liquid but also as gelled rocket propellants [36],[37].

4. PHYSICAL PROPERTIES

Due to the non-Newtonian rheological behavior of gel propellants special attention must be paid to their influence on flow, spray and combustion behavior and vice versa. Thus a very close coordination is necessary between all steps in the development process on the way to develop a gel rocket or ramjet engine, which is visualized in the sketch of Fig. 2.

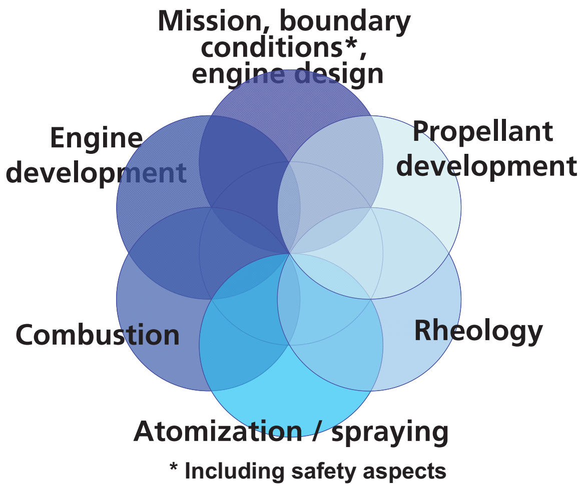
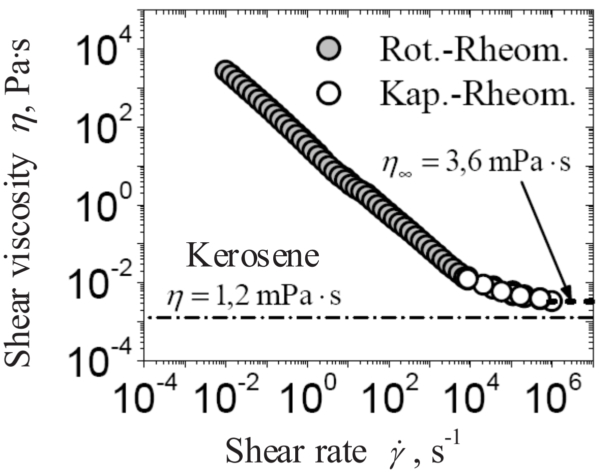


Figure 2. Gel technology development network

Within the scope of this chapter the state of the art of various relevant aspects of research and technology development will be presented.

4.1. Rheology and flow behavior

Gel fuels and propellants can be described as shear-thinning fluids. Their shear viscosity decreases with increasing shear rate up to a minimum value, which is called upper Newtonian plateau, as can be seen for example for a JetA-1/Thixatrol gel in the upper diagram of Fig. 3. This plateau is often located near the viscosity of the basic fluid to be gelled. Thus it is obvious that with sufficient high shear rates in the range up to 10^5 or 10^6 s^{-1}, which can be produced with distinct injector types, a sufficient liquefaction for flow and spray processes can be reached.



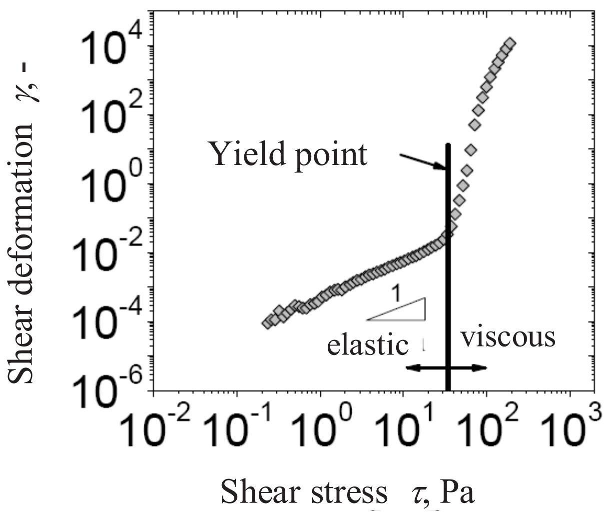


Figure 3. Dynamic shear viscosity η vs. shear rate $\dot{\gamma}$ (top) and determination of the yield stress (down) for a JetA-1/ThixatrolST gel [40]

Several gels show a distinct viscoelastic behavior. This arises from the microscopic structure as for example from very long entangled molecules of several organic gellators. 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. [38],[39].

If an applied shear stress is below the material dependent yield stress, a gel behaves to a large extent elastic and only if the applied stresses are higher than the yield stress the viscous properties become dominant and the gel starts to flow. This can be seen in the lower diagram of Fig. 3. The elastic range is represented by a gradient of 1, where the shear deformation is proportional to the applied shear stress. Thus a gel is elastic under low applied shear stresses as long as its yield stress is not exceeded and is viscous with diminishing viscosity as the shear rate is increased.

The shear viscosity / shear rate ($\eta / \dot{\gamma}$) 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) [40],[41]

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

whereas τ_0, K, n and η_∞ are material-dependent constants.

The velocity profile of gels flows in tubes of constant diameter is on the one hand broader than that of Newtonian fluids, because the gel flow has a higher velocity gradient near the wall. On the other hand 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. Based on the HBE equation Madlener et al could derive analytically a generalized Reynolds number. Furthermore they could determine numerically the characteristics of the critical Reynolds number, which give information about the transition from laminar to turbulent flow conditions. They found 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. Further information is given in Refs. [40]-[44].

Generally it can be said that elasticity influences the extensional behavior of a fluid. In a pure extensional flow the elements of a fluid can be stretched or squeezed. The extensional viscosity η_E of a Newtonian fluid is constant and its value is 3 times that of the shear viscosity, as described for example in Ref. [8]. For non-Newtonian fluids, however, it can be significantly higher. Viscoelastic fluids are generally extensional thickening fluids, because their extensional viscosity η_E increases with increasing strain rate $\dot{\varepsilon}$ [38],[39].

The thixotropic behavior has also to be mentioned in relation to gel propellants. Thixotropy means that the shear stress and thus the shear viscosity of a fluid decrease with time if a constant shear rate is applied (under constant temperature conditions). Also in case of recreation an increase of shear stress and viscosity occurs if a constant shear stress is taken away. Rahimi and Natan investigated inorganic gel fuels and they found that the viscosity decrease with this gel type can be assumed as insignificant in typical lengths of rocket motors [45]. Based on this finding thixotropic effects seem to be of minor importance for the investigated inorganic gel types. Nevertheless it should be mentioned that the injectors and feeding lines should be designed in a way that too strong shear rate gradients (caused by too quick size reductions of gel flow cross sections) should be minimized.

4.2. Spray behavior and propellant injection treatment

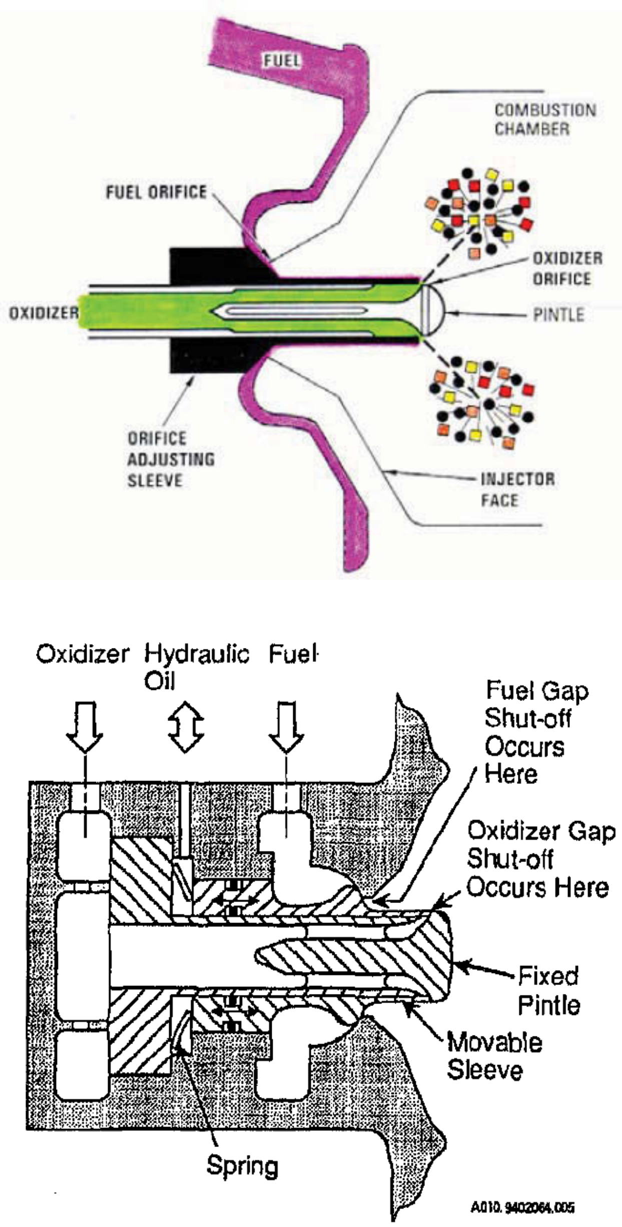


Figure 4. Top: Principle sketch of pintle injector concept for Newtonian propellant combinations [46]; Bottom: Sketch of engine face shut-off injector for gel propellants [47]

In literature it is described that several different injector types were used for the atomization of gel propellants. Hodge et al [2],[3] used a pintle injector, with which they introduced a hypergolic combination of gelled hydrazine and gelled nitric acid via two fluid flows into the combustion chamber, where they interact. A simple principal sketch of a pintle injector for Newtonian fluids together with a sketch of a version for gel propellants can be seen in Fig. 4. By moving of the orifice adjusting sleeve the fuel and the oxidizer orifices can be opened or closed simultaneously. Detailed information about injector design and performances with this gelled fuel/oxidizer combination is not given in the here cited papers, but further information about the flight demonstrator will be given in chapter 5.

Robers et al [48] investigated air-blast atomizers, but they found that very high impulse ratios of the surrounding air flow to the gel flow are necessary for a sufficient breakup of a gel jet. Also they have shown that not all gels can de disintegrated to droplets. Several gels decay only to fiber or thread-like structures, which have a significantly lower surface area in comparison to a droplet phase.

Natan et al investigated various impinging jet injectors, whereas in several cases air was fed through the outer injector orifices of a linear triplet so that this kind of injection can be put both to impinging jet injectors and to air blast or air assisted atomizers, see e.g. Ref. [49]. Additionally they investigated the influence of periodic disturbances, which were introduced in the jets at the injector exit plane by rotating toothed discs. They found that smaller average droplet diameters occur with increasing rotational speed [50].

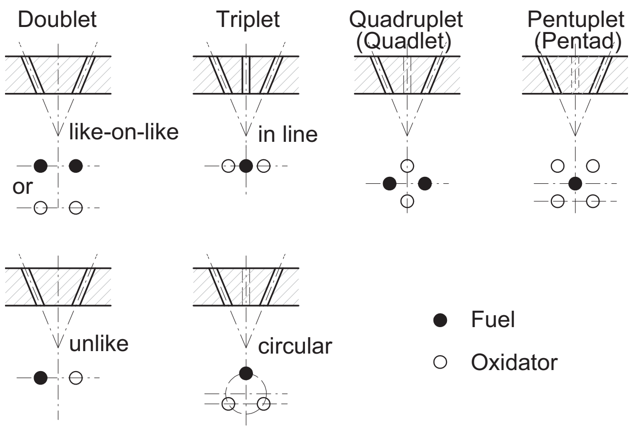


Figure 5. Some examples of impinging jet injectors

Impinging jet injectors were used by several authors for the atomization of gelled propellants and simulants. To all types it is common that two or more fluid jets are impinging on each other and decay downstream from this impingement point as can be seen e.g. for a like-on-like doublet on the shadowgraph images of Figure 6. Figure 5 shows the sketches of several examples. Impinging jet injectors are typically used in engines with propellants that are storable under ambient pressure and temperature conditions. These injectors are easy to manufacture and high shear rates are produced both in the injector passages and the region where the gel jets collide.

Various sub-types were tested, whereas the doublet was investigated in most detail. The atomization of gelled propellants and simulants with doublet injectors was investigated by several authors and will be described later on in this chapter. Triplets and quadruplets were investigated e.g. by Natan [51]. An unlike quintuplet (= pentuplet) was used by Peretz et al [52], but only combustor investigations are reported.

Figure 6 shows the breakup behavior of a kerosene/ThixatrolST gel with a doublet like-on-like impinging jet injector. Each pair of shadowgraph images shows the perpendicular view on the injector and the developing spray at different jet exit velocities and different calculated generalized HBE Reynolds numbers (based on the HBE equation), previously presented in Ref. [53]. It is obvious that with increasing jet exit velocity smaller droplets are produced. The atomization of this and various other gel types is effective and average droplet diameters similar to Newtonian liquids could be reached under distinct experimental conditions as the measurements presented in Fig. 6 have shown, see e.g. Ref. [54].

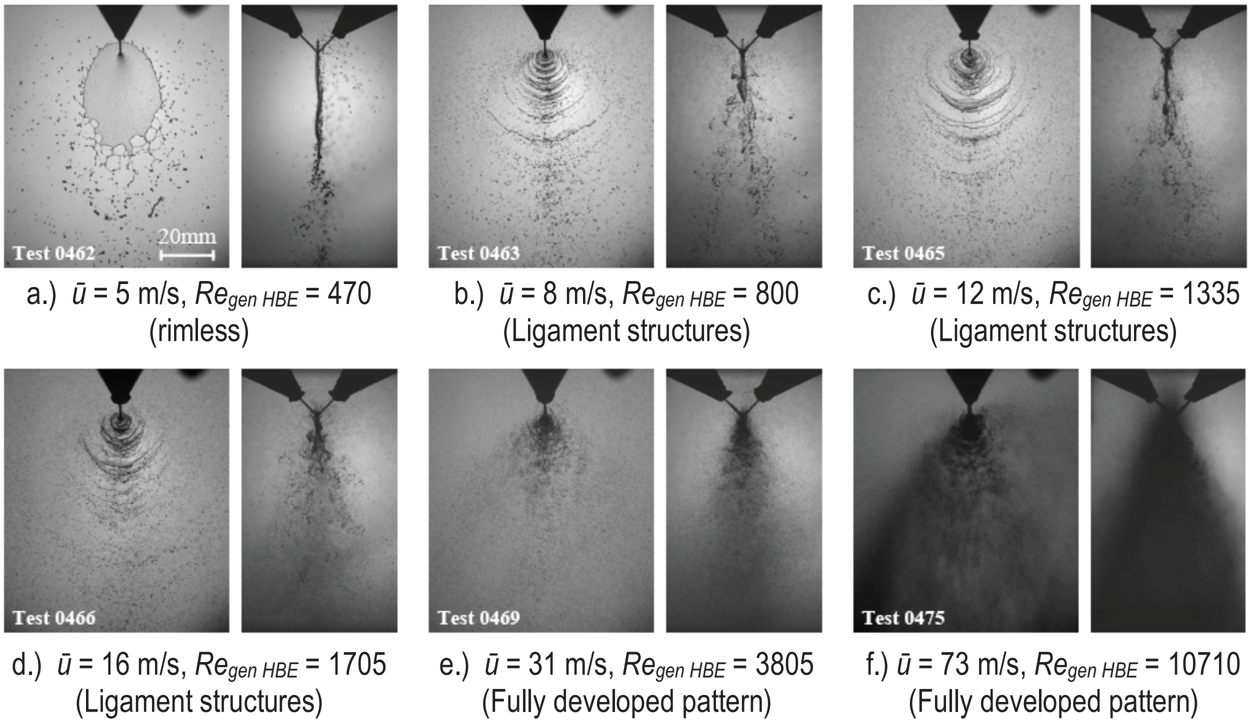


Figure 6. Break-up process of a kerosene/ThixatrolST gel with a doublet like-on-like impinging jet injector in dependence of injection velocity and the generalized HBE Reynolds number [53]

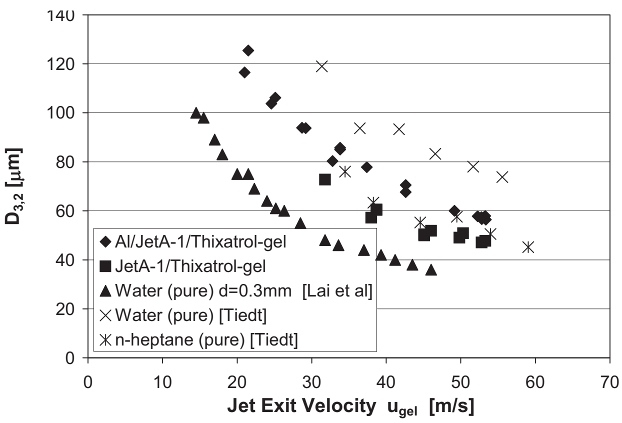


Figure 7. Average droplet diameter (Sauter mean $D_{3,2}$) vs. jet exit velocity u_{gel}. Impingement angle 2θ=90°; injector exit diameter d=0.7 mm [54]. For cited literature in this diagram please see Ref. [54].

Detailed investigations about the spray and combustion behavior of gels with metal particle addition were also conducted. The results show that for smaller particles the influence of the particle diameter on droplet diameters seems not to be very pronounced. It should be mentioned in this context that particle diameters should be significantly smaller than injector diameters because of the danger of blocking. For more detailed information please see e.g. Refs. [17],[55]-[57].

As previously mentioned several gels cannot be atomized to small droplets with impinging jet injectors under the used common conditions. Thread- or fiber-like structures are formed instead, which have a significant smaller surface area than a droplet phase. This behavior can in some cases partially be related to the existence of a distinct elasticity of these gels [38], whereas the authors mentioned that further investigations are necessary for a better understanding of the formation of threads instead of droplets.

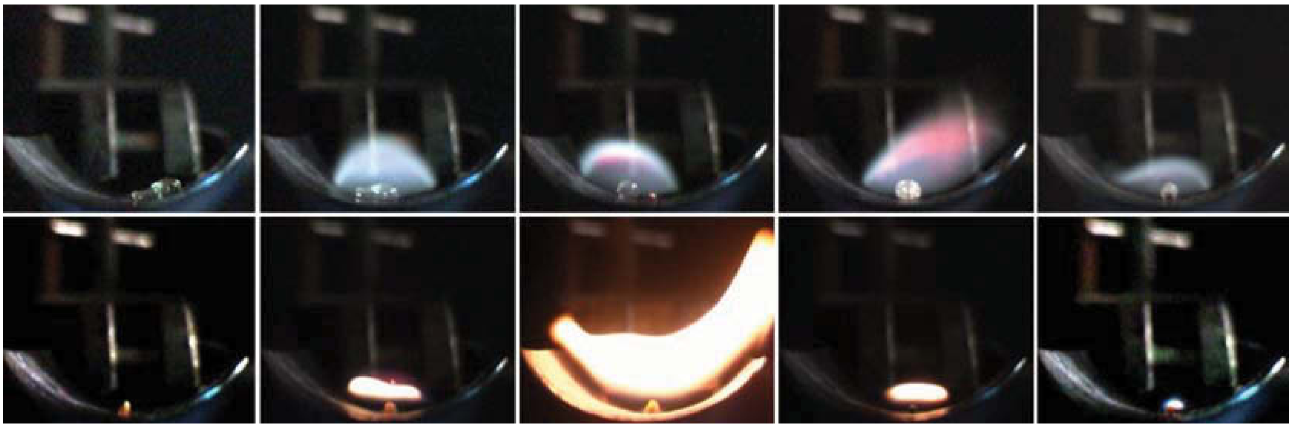


Figure 8. Combustion of a single droplet of nitromethane gelled with guar gum [60]

4.3. Combustion behavior

4.3.1. Single droplet combustion

The combustion of gelled propellants is closely related to droplet or spray combustion. When dispersed into the burning chamber the gel drops may be larger and less symmetrical spheres than liquid droplets but the combustion is also controlled by the heat flux from the flame zone to the droplet that affect heating and vaporization or initiate decomposition. The higher viscosity of gelled propellants also under shear stress conditions hinder the internal flow inside the droplet and may slow the heating. But especially in the case of metallic fillers this effect may be neutralized by increased heat conductivity and higher flame temperatures, see Refs. [16],[31]. The gelling agents that often consist of solid particles or organic material which tend to carbonization may accumulate at the droplet surface and strongly influence the combustion behavior.

Several gelled propellants are burnt as bipropellants that mainly ignite hypergolic. For the combustion of a bipropellant combination the fuel and the oxidizer have to be brought into local contact by diffusion processes so the combustion time that mainly influences the size of the burning chamber is strongly controlled by dispersion and mixing. The physical process can simply be described by the Spalding theory [58]. Nathan summarizes the combustion of gelled bipropellants in his comprehensive review [1]. He also observed that the gelling agents encrust the droplet surface and hinder reaction between fuel and oxidizer [59]. The resulting shell may be broken by boiling and micro explosion.

By a concerted selection of gelling additive this effect can be avoided. E.g. Weiser [60] showed that nitromethane gelled with agar-agar burns in air without forming such a shell. When all NM is consumed a carbonized spherical residue remains, which burns out slower than the energetic fraction.

Recently also an increasing number of gelled monopropellants is suggested [61],[62]. Such propellants burn in a certain analogy to solid propellants featuring a constant regression rate, which is characteristic to the propellant composition and which depends on chamber pressure and initial temperature [31]. At least this is valid in an initial phase until the droplet temperature reaches the boiling point. So the combustion time is mainly controlled by the initial droplet dimension. At the boiling point a swelling of the droplet size by bubbling followed by fragmentation due to micro explosions were observed [60].

Louazé [63] and Sabourin [30] investigated the behavior of fumed silica during combustion of NM gels. They observed molten residues formed inside the condensed phase of the propellant. High-speed macro images of burning droplets confirmed this and showed that the silica agglomerates inside the condensed phase of the burning droplet which is cooler than the melting point of silica.

4.3.2. Combustor experiments

A large number of test setups exist for the investigation and the development of combustor processes with gel propellants and for engine development. Due to limited space only three setups will be presented in this subchapter as examples.

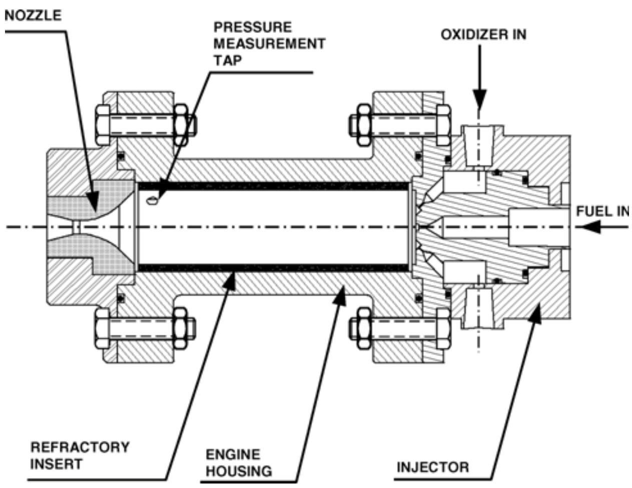


Figure 9. Schematic of experimental gel-propellant rocket engine at Rafael [52]

Peretz et al [52] developed a laboratory-scale (model) combustor with a single pentuplet unlike injector, where four IRFNA oxidizer gel jets impinge on one MMH fuel gel jet. The sketch of this combustor is presented in Fig. 9. The combustion pressure ranged between 20 and 35 bars. Maximum *c** efficiency of more than 90% was obtained in continuous firings. Also could be shown with the hypergolic gel combination in multipulse operations of up to 20 cycles the successful on-off characteristic.

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 can be conducted. The facility can be equipped with different modular model combustors and injector heads to allow detailed work on handling, feeding, ignition and combustion of gelled propellants. A H_2/O_2 burner can be attached to the mounted model combustor so that also non-hypergolic propellants can be ignited. The investigated gel propellants, which were developed by the Fraunhofer-Institute of Chemical Technology ICT, can also be produced and enhanced on-site.

The gel propellants are 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. The conducted experiments showed the thrust modulation capability by varying the gel mass flow rates. With the conducted experiments within the scope of combustor process development operational ranges for investigated propellants within the chosen experimental setup could be determined. Figure 10 shows a typical test run.

Figure 10. Test run of a gel model rocket combustor at DLR at Lampoldshausen

Beside the work on a combustor equipped with a pintle injector at TRW detailed work on the development of an impinging stream vortex engine (ISVE) was conducted in the USA. This vortex engine offers an alternative to conventional combustion chambers. Two schematics of the experimental setup can be seen in Figure 11. In this combustor the propellants are injected tangentially to the chamber wall, impinge, and then swirl via the vortex flow that is generated by this tangential injection component. The initial mixing occurs during stream impingement and the final mixing occurs in the highly turbulent vortex region between the injector orifices and the chamber walls. Nusca et al [64] report that tests with the ISVE yielded delivered specific impulse efficiencies of 250-255 sec for an L^* of 5 inches using inhibited red fuming nitric acid (IRFNA) as oxidizer and 50 percent carbon-loaded monomethyl hydrazine (MMH) as the fuel. Due to the unconventional combustor geometry detailed numerical calculations were conducted beside experimental work, see e.g. Refs. [64]-[66].

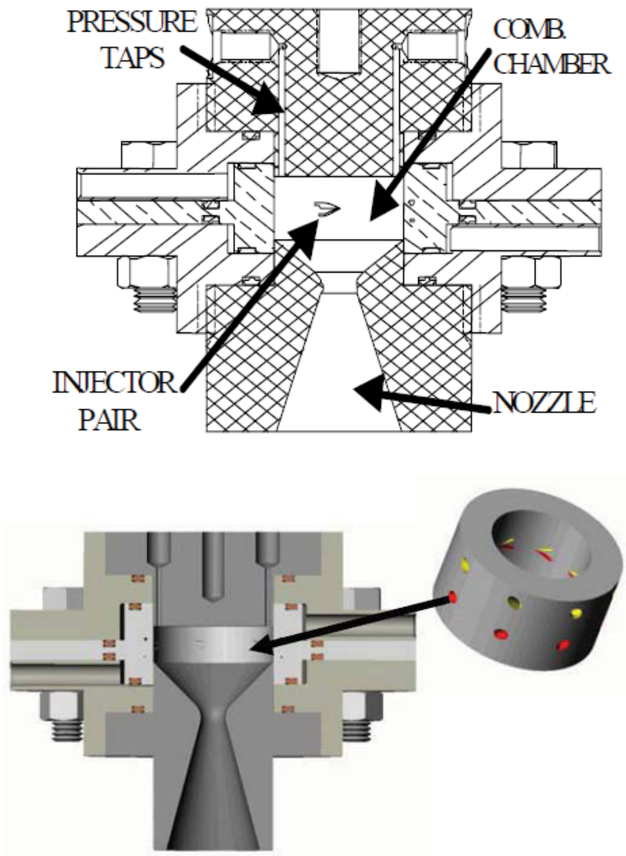


Figure 11. Vortex engine. Schematics of the ISVE in an engine test block [64]

5. REPORT OF ACTIVITIES

In this chapter a very short overview about gel propulsion activities in several countries will be given, whereas only some in open literature available examples can be cited. It has to be mentioned that since some years an increasing interest in this theme can be observed worldwide.

5.1. United States of America

Since ca. the 60`s of the last century work on solid loaded fuels was conducted in the USA, see e.g. Refs. [67]-[71]. This early work was focused at US Air Force on hydrazine gels with aluminum and beryllium particles for liquid rocket and advanced propulsion systems and at the US Navy on hydrazine / nitric acid bipropellants. After a decline in the mid of the 70´s of the last century the interest in gels increased again in the 80´s due to new demands on the development of future propulsion systems like thrust and energy management, insensitive munitions (IM) criteria, fuels with high energy density, low toxicity, improved handling and storage safety, low over-all life costs, etc. The first successful flight demonstration of a gel fueled rocket engines was conducted by TRW in 1999 and 2000, whereas they used a hypergolic combination of a loaded

MMH fuel gel and a IRFNA oxidizer gel [2],[3].

Figure 12. First launch of a gel missile [2]

Research and technology development activities were conducted in USA in the last decades at research organizations, universities and companies with a main focus on various gelled hypergolic combinations of MMH/IRFNA or similar species like UDMH, and NTO. But also stimulant gels, which should offer the possibility of easier and safer basic research, were used. A further research area was cryogenic gels of e.g. hydrogen, partly with metal particle addition, which were proposed mainly for civil in-space applications. For further information, please see e.g. Refs. [1],[18]-[20],[37],[47],[67]-[69].

In 2009 two MURI programs (Multi University Research Initiative) were initiated, which deal with basic and applied research relevant for gel propulsion. First results were presented e.g. at the Joint Propulsion Conferences in 2009 and 2010, see beside the publications, which are cited in the previous chapters, also the following references as examples [70]-[72].

5.2. Israel

Since ca. one and a half decade detailed research and combustor development work on gel propulsion is ongoing. The research activities at the Technion cover the whole spectrum with analytical, experimental and numerical work on rheology, spray behavior, combustion of single droplets, ignition and combustion. The investigated propellants cover metallized (aluminium, boron, etc.) and non-metallized gels. Many publications exist, where only few could be cited in the previous chapters.

Peretz et al [52] developed a model combustor with an unlike quintuplex impinging jet injector making use of gelled MMH and gelled IRFNA. Since 2010 also a gel fueled ramjet model combustion chamber was commissioned for combustion process investigations at the Technion [73],[74].

It should be mentioned that a detailed overview of the worldwide work on gel propulsion up to the year 2000 was published by Natan and Rahimi [1]. An short overview about research activities at the Technion in the year 2005 is given in [75]. Beside the Israeli publications, which are cited in the previous chapters, also the following references should be cited as further examples [76]-[79].

5.3. Germany

Basic research activities on gel propulsion began in 1999 at DLR-Institute of Space Propulsion. In 2001 the German Gel Technology Program was started with the aim to develop the necessary technology to build a gel propellant rocket engine and to demonstrate its capabilities by a demonstration flight within a decade. Partners in this program are the Institute of Space Propulsion of the German Aerospace Center DLR, the Fraunhofer-Institute for Chemical Technology ICT, the Bayern-Chemie, the German Forces testing facilities and the German Federal Office of Defense Technology and Procurement (BWB). Basic research activities cover gel propellant development, aging, rheology, flow behavior, spray and combustion behavior. Based on these activities detailed technology development work was conducted for the combustor process, the gel rocket engine with feeding system and the demonstrator missile. The structure of this program and obtained results up to the year 2008 were presented at the German Aerospace Congress in 2008 [4] and the further progress at the following congress in 2009 [5]. Results from the basic and applied research activities have partly been presented in the previous chapters of the present publication. Within the scope of the current chapter 5.3 the flight demonstration activities will shortly be presented below.

Figure 13 shows the sketch of the principal system layout of a GRM which was developed and built by Bayern-Chemie. The propellant is fed by high-pressure gas that in this case is produced by a small solid propellant gas generator. Pressurization by inert gas is possible as well. The thrust is controlled by a propellant flow throttling device.

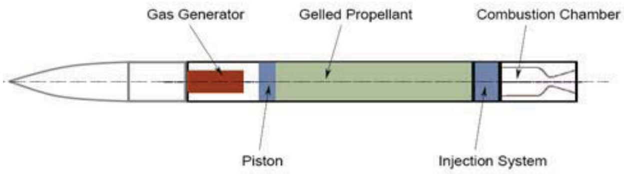


Figure 13. Principal system layout of a gel rocket motor (GRM)

Special features of the German GRM are mission-adapted thrust modulation, good insensitivity, low plume / trail signatures, “green” propellants, environmentally friendly exhaust products and the possibility to build explosive-free rocket motors and reusable rocket motors. The technical basics and the rationale that drives the development of GRMs as well as the history have been presented at the German Aerospace Congress 2008 [4].

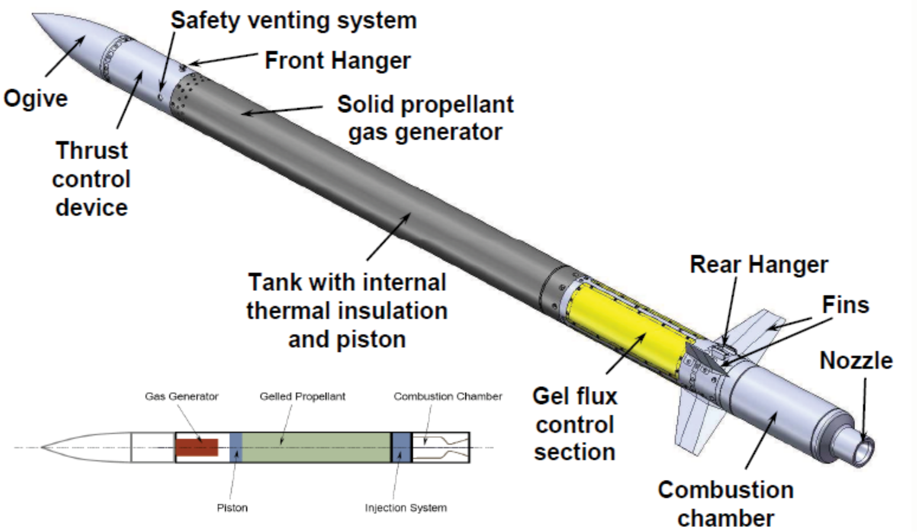


Figure 14. The flight demonstrator missile (TD-F)

Based on the activities described in Ref. [4], a GRM for the flight demonstration and a missile have been designed, built and verified. The flight demonstrator missile is shown in Figure 14. It has a cylindrical cross-section with an ogival nose. The caliber is 135 mm, the length 3042 mm, and the propellant mass is 12 kg. The comparatively high mass of 75 kg limits the range to about 10 km, thus limiting the safety area as well. In addition the massive structures give a fair chance to recover the missile in a stat that allows a thorough expertise of the parts and components after the flight test. The stabilizer fins are canted to create a spin of up to ten rounds per second. This makes sure that any asymmetries of the airframe or thrust vector anomalies do not cause linear aberrations from the course. Because a ballistic flight is sufficient for the demonstration of the propulsion system, the fins are fixed. The front and rear hangers are designed to separate from the rail at the same moment in order to prevent a pitch-down when the missile leaves the rail. The electronic control is equipped with a data storage that allows reading out the data that have been recorded during the flight, if the missile suffers not too severe damage upon impact.

Some components had to be adapted for the flight demonstration, e.g. the gel flow control valve with actuator and the on-board computer that controlled the valve in order to produce a pre-programmed high – low – high thrust sequence. Mandatory was a safety venting system that released the tank pressurization gas through two opposing orifices in case that

- the tank had been emptied from gelled propellant
- the launch sequence was stopped, or
- the missile impacts at the end of its flight upon the earth surface

in order to make sure that the missile could be recovered safely after the flight.

All components have been tested against vibrations, shocks and by static tests.

Figure 15. The GRM demonstrator missile at launch

The flight test was carried out at the German Armed Forces proving ground at Meppen in cooperation with WTD 91, who besides the test area provided the testing staff, the installations of the launch site and the complete set of optical and radar measuring equipment needed to observe the flight and measure flight trajectory and missile velocity. Two perfect flights verified all functions of the GRM and the missile at December 2, 2009. Figure 15 shows one of the two GRM demonstrator missiles at launch.

The demonstration flights concluded the first phases of the German GRM technology program and showed that an initial operational capability has been achieved and that the GRM technology is ready for first applications. Nevertheless, work will go on to improve the functions and the performance parameters in order to enlarge the field of potential applications of GRM technology.

5.4. Other countries

Also activities on gel propulsion from several further countries are published. In India basic research on gel propulsion is conducted since some decades at several places, whereas mainly work on hydrazine and nitric acid gels was published. For further information please see e.g. Refs. [80],[81]. In China also work is conducted, which is mainly written in Chinese, see e.g. [82]-[84]. Only very basic research activities were conducted in Great Britain, see e.g. Ref. [85]. Furthermore it should be mentioned that work is conducted in several countries on hybrid rockets, whereas gelled oxidizers seems partly be of interest [86].

6. FUTURE POSSIBILITIES AND PROPOSALS FOR APPLICATIONS

Based on the successfully conducted flight tests of the demonstrator missiles it can be said that the GRM technology is now ready for first applications, for example launch motors for drones or cruise missiles with turbojet propulsion systems [87],[88].

For these applications, ballistic performance is secondary compared to other criteria like cost per launch, logistic simplicity, insensitivity and environmentally friendliness. Figure 16 shows the concept of a reusable launch motor for drones. Figure 17 presents arrangements for the launch of heavy cruise missiles, where the GRM allows arranging the motor and the tanks according to the available space. In a similar way, the insensitive GRM technology could make rocket assisted take-off an interesting option for military transport aircraft if evacuation operations with full load from marginal landing strips, maybe in poor and muddy condition, are envisaged.

Figure 16. Concept of a reusable launch GRM for drones and UAVs

In the medium term, GRMs have the potential to be used as sustain motors for missiles that travel at subsonic or low supersonic cruise speed and benefit from the capability to adapt the thrust to maneuvers and to trajectories with climb/descent phases or to accelerate when approaching the target [89]. Under certain conditions a missile with the same GRM could be fired from different platforms, which could be a firing station at rest, a ship, a hovering helicopter or a fixed-wing aircraft in fast flight. The duration of the boost phase can be adapted to the velocity and altitude of the platform. If the platform is a fast flying fixed-wing aircraft, a minimum boost phase to separate the missile from the aircraft is sufficient and the propellant not needed for the boost phase can be used to extend the range of the missile. If that missile is fired from a canister at rest, the maximum range is less due to the longer boost phase, but the same GRM could be used. In short: a GRM could be an important contribution on the way to generate true modular missile designs.

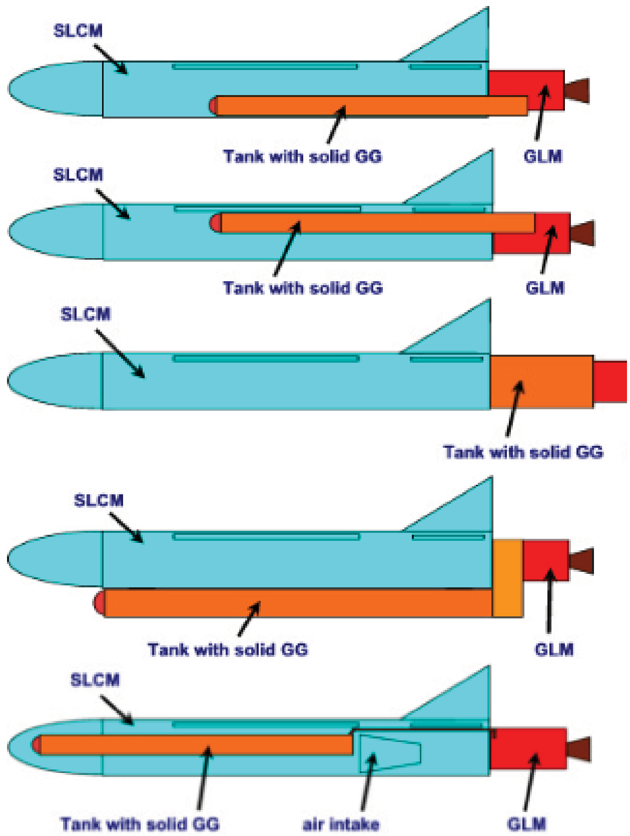


Figure 17. Possible configurations for launch motors of heavy cruise missiles

In the longer term, throttleable gas generators with gelled propellants should be available for many applications, e.g. direction and attitude control thrusters for kill vehicles that engage ballistic missiles or their warheads. For example Olson et al [67],[90] reported of the progress of a program about the development of a gel propulsion control system for kill vehicles, which was conducted in the first half of the 90s of the last century. This system, which can be seen on the sketch of Fig. 18 worked with gelled MMH and gelled RFNA. Another concept with a controllable gas generator and monopropellant was proposed by Naumann et al [91].

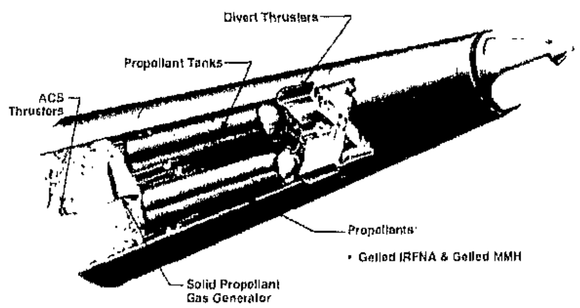


Figure 18. TMD gel DAC subsystem concept [90]

A significant benefit of the German propellant concept compared to contemporary techniques with liquid or gelled MMH/RFNA or similar propellant combinations is the high degree of insensitivity or the low hazard potential at production, deployment and use. With an improvement of specific impulse and an increase of propellant density, GRMs should be a real alternative even for general missile propulsion systems.

In the following some in literature presented proposals for the use of gel propellants are presented here. Gavitt and Fritz presented the development of a MMH/IRFNA gel propulsion system for escape systems [47]. Pickl proposed a crew escape system, which makes use of gel propellants [92]. Maybee and Krismer reported in [93] about a hydrazine based gel pressurization system [94].

It should also be mentioned that in several publications in-space applications are proposed, which deal with cryogenic gels. For example Palaszewski et al [95],[96] proposed metallized cryogenic hydrogen based gels like H_2/Al mainly together with LOX. The authors described that these propellants could be used e.g. for manned or unmanned Mars exploration missions because of theoretical launch mass reductions. Also for Mars ascent vehicles hypergolic gels were investigated in a concept design study [97]. Due to the more difficult handling characteristics cryogenic as well as hydrazine based gels are not within the main focus of the present publication.

For sample return missions to Mars research is also ongoing to develop a return thruster, which makes use of aluminium powder, which has to be brought with from earth, and carbon dioxide from the Martian atmosphere. Shafirovich [98] proposed to gel the sampled CO_2 and embed the Al particles. It should be mentioned that the onboard production of a metallized gel under pressures above the critical point of CO_2 is a challenging task.

Beside the classical gel rocket application the use of gel fuels in hybrid rockets was investigated by Brandenburg and Elzooghby, who replaced the solid fuel grain by an ethanol gel based fuel grain [99].

With a view to a more closer surrounding other applications in the civil field could be for example scientific sounding rockets, where cost, easy logistics, insensitivity and environmentally count more than a minimized launch mass. The use as a first stage, maybe with a re-usable rocket motor could be a reasonable initial application. The capability to adapt the thrust level and to shut off the GRM in combination with the aforementioned properties could make the GRM interesting for orbital insert propulsion systems or for final stages of scientific launchers that have to provide an accurately defined velocity increment to reach a precisely defined velocity and altitude. Furthermore re-usable small strap-on boosters with simple handling characteristics (no MMH/RFNA gels) could be interesting, if thrust densities similar to propellant formulations, which are in service, together with similar system masses could be realized.

For the application of gel propulsion to future space related applications several technological hurdles have to be overcome. They are primarily:

- Reliable ignition and possibly re-ignition of gel propellants under vacuum or vacuum near conditions. For this task either gelled hypergolic F/O combinations or additives could be interesting.
- In the case of re-ignition injectors could be necessary, which can be closed to avoid the vaporization of the basic fluids in a way that residues of the gellant remain in the injector orifices. For a first start or if there should be only a one time ignition the motor can be sealed by an ejectable cover or a burst disc so that higher pressures are available.
- Additives and/or other propellants (combinations), which
  - enhance the specific impulse significantly above the current level, which is for the German demonstrator similar to that of double base propellants. Additives like metal particles or hydrides seem to be interesting.
  - lead to a hypergolization, if bipropellants shall be used. This is helpful to avoid ignition devices, especially for missions with re-ignition. E.g. Natan proposed to add a solid catalyst to gelled kerosene for a bipropellant combination with gelled H_2O_2 [79].
- Reduction of mass so that the gel propulsion systems will have a similar mass and volume similar to liquid propulsion systems. This could be realized by e.g.
  - lighter structures of the up to now massive tank
  - reduction of the viscosity level of propellants immediately before start e.g. by microwave excitation [100]. This leads to reduced feeding pressures and thus lighter structures. The easy storage and handling characteristics will not be affected by this late excitation.
- Avoidance of highly toxic and/or aggressive species like MMH/RFNA or similar combinations. These combinations demand a cost-intensive handling at ground as for example during gel production and fueling

The advancement of the gel propulsion technology to overcome these technological gaps together with the easy handling and storage characteristics and the throttleability and/or reignitability could make gel propulsion systems attractive also for space related application.

7. SUMMARY, CONCLUSION AND OUTLOOK

Summarizing the state of art of research and technology development it can be said that the technology is now ready for first applications. These applications could actually be primary in the missile area but others like escape systems seem also to be promising. For space applications some technology tasks have to be solved so that gel propulsion systems can get attractive and can play off their advantages.

A significant benefit of the German propellant concept compared to contemporary techniques with liquid or gelled MMH/(I)RFNA or similar propellant combinations is the high degree of insensitivity or the low hazard potential at production, deployment and use. With an improvement of specific impulse and an increase of propellant density, GRMs should be a real alternative even for general missile propulsion systems.

Gelled energetic ionic liquids are also interesting because of their good thermal stability, electric conductivity and extremely low vapor pressure. Due to the very low vapor pressure a significantly reduced environmental risk and better storage and handling properties are expected combined with higher performance. They also enable an increased operation temperature range compared to conventional monopropellants.

Actual activities within the German Gel Technology Program focus on several topics. Several goals are to improve like the
– specific impulse
– density of the gel
– volume of the combustion chamber
– ratio of combustor diameter to nozzle throat diameter
– thrust turn-down ratio, i.e. the pressure limits of stable combustion, and
– time of operation of the combustion chamber

The activities are ongoing and first results will be expected in the near future.

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9. NOMENCLATURE

$D_{3,2}$	Average droplet diameter (Sauter mean), m
K	pre-exponential factor in HBE equation, Pa·s^n
n	exponential factor in HBE equation, -
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

Abbreviations

GG	gas generator
GRM	gel (propellant) rocket motor
GLM	gel (propellant) launch motor
HBE	Herschel-Bulkley Extended
IRFNA	inhibited red fuming nitric acid
ISVE	impinging stream vortex engine
LOX	liquid oxygen
LRM	liquid rocket motor
MMH	monomethyhydrazene
RFNA	red fuming nitric acid
RM	rocket motor
SLCM	surface launched cruise missile
SRM	solid rocket motor

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