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Preliminary Tests on Thermal Ignition of ADN-based Liquid Monopropellants

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Abstract

Preliminary tests on thermal ignition with ADN-based liquid monopropellants FLP-106 and LMP-103S have been conducted with two thermal ignition methods. Investigated thermal ignition methods were based on a pilot flame igniter and on a glow plug. Results indicated that ADN-based propellants offer different behavior compared to conventional monopropellants. At first the propellants need to be conditioned by evaporating the water portion. In this phase the heat transfer from the igniters into the propellant play a major role for the ignition time delay. After evaporation of the water the propellant decomposition can be initiated. It was found that with the thermal igniters the internal energy feedback from decomposing propellant portions is insufficient to condition newly injected propellant portions upstream. An external heat feedback is necessary to sustain water evaporation and hence propellant combustion. While tests with a pilot flame igniter and a cylindrical combustion chamber were not successful, ignition via a glow plug showed satisfying decomposition and ignition behavior. With the conducted preliminary thermal ignition tests a profound knowledge could be gained concerning propellant ignition behavior of FLP-106 and LMP-103S. Furthermore similarities and differences of both propellants could be analyzed and allow improvement of thermal ignition methods for future research activities.

1. Introduction

For the last 60 years hydrazine and its derivatives were the standard propellants for satellite and orbital propulsion systems. In 2011 the European Union classified hydrazines as substances of very high concern (SVHC) in the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) regulation [1]. Hydrazines are not only highly toxic and carcinogenic thereby complicating transport, handling and safety procedures; furthermore production waste disposal drastically increases life cycle costs. Consequentially there is a growing effort in finding and qualifying substances to replace hydrazine propellants with less-toxic and lower-priced propellants. Some promising candidates include aqueous multicomponent-solutions of ammonium dinitramide (ADN) [2, 3] or hydroxylammonium nitrate (HAN) [4], concentrated hydrogen peroxide, blends of hydrocarbon fuels and nitrous oxide [5] or energetic ionic liquids (EIL) [6].

European research focuses mainly on the investigation of ADN-based propellants. The most mature ADN-based liquid propellants are FLP-106 and LMP-103S, the latter one being qualified by the European Space Agency (ESA) at the moment. In contrast to hydrazine both ADN-based propellants are aqueous multicomponent mixtures leading to different propellant characteristics regarding fueling, spray behavior, ignition and combustion phenomena. [7]

1.1. State of the Art

So far thrusters with ADN-based liquid monopropellants are ignited via preheated catalytic beds. The preheating to 350 °C requires time and in fact ADN-based thrusters are not cold-start capable like mature hydrazine thrusters [8]. Furthermore, when scaling up to larger thrust classes the needed preheating energy for ADN-based thrusters rises drastically. Also combustion temperatures of ADN-based liquid monopropellants are significantly higher than in hydrazine thrusters. For example combustion temperature of LMP-103S is 1630 °C instead of approximately 900 °C

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for monopropellant hydrazine. The usage of high temperature materials like rhenium or iridium is in fact unavoidable and also the catalyst must sustain these temperatures without degradation. By using a thermal igniter the delay time due to preheating could be improved or overcome. Moreover with thermal ignition the need for a high temperature sustainable material for the decomposition of the propellant gets redundant. Depending on the purpose of the thruster different thermal igniters could be of interest. Thrusters for orbit-raising as well as for de-orbiting only need few ignitions whereas for reaction and attitude control (RACS) thrusters as well as for attitude and orbit control systems (AOCS) re-ignitability is a key aspect. The most interesting thrust segment for liquid green monopropellants combined with a thermal ignition system is the 200 N thrust class. [7]

To the authors' knowledge, to date, there are no results on feasibility of sole thermal ignition of ADN-based liquid monopropellants in thrusters, combustion stability and sustainment. In the present work preliminary testing is done for two thermal ignition methods. The first method is an ignition via a torch igniter creating a pilot flame in the combustion chamber and thereby simulating a pyrotechnical ignition. This ignition method is of interest for de-orbiting or orbit-raising. The second investigated method is based on a glow plug ignition and could be used for multi-start operation purposes for orbital propulsion systems.

1.2. General information on ADN and ADN-based liquid monopropellants

Ammonium Dinitramide (ADN)

ADN is a white crystalline solid, which has the chemical formula $NH_4\,N\,(NO_2)_2$. It is an energetic substance which currently has an UN transport classification of 1.1D. ADN is highly hygroscopic and therefore can be perfectly dissolved in water. For solid propulsion applications this property is extremely undesired. In contrary for liquid propellant applications water not only fulfills the task to liquefy the propellant, furthermore it mitigates the explosive properties of ADN [9].

LMP-103S

LMP-103S is the most mature propellant blend based on ADN and so far has been used for over 150000 successful test firings in over 70 thrusters ranging from 100 mN up to 200 N. Its first space use was demonstrated in the PRISMA satellite in 2010. It is manufactured by ECAPS AB, a subsidiary of the Swedish Space Corporation (SSC). LMP-103S is composed of 63 % ADN, 14 % water, 18.4 % methanol and 4.6 % ammonia. [3, 10, 8]

FLP-106

FLP-106 is the second mature propellant blend invented by the Swedish FOI in cooperation with SSC. FLP-106 consists of 64.6 % ADN, 23.9 % water and 11.5 % MMF. The vapor pressure of FLP-106 is estimated to be below 21 mbar at 25 °C. [10, 11, 12]

3. Experimental Tests and Setup

The thermal ignition research was conducted at the test facility M11 at DLR site Lampoldshausen. The test setup consisted of a feeding and support system of the test bench and the different ignition demonstrator setups.

3.1. Feeding and Support System.

The test position supported a propellant and flushing supply to the ignition demonstrators. A schematic fluid plan of the test bench, fluid and gas system and the interface to the ignition demonstrator setup is shown in Figure 1. The propellant system included a stainless steel propellant tank with a maximum capacity of 2 liters and a Flow Control Valve (FCV). For the whole setup stainless steel piping's and flexible hoses with an inner diameter of 4 mm. Pressurization of the propellant was realized using a GN_2-pressure regulator. For the tests presented in this paper a constant tank pressure during the tests was used. The propellant feeding system was instrumented with a pressure transducer type Kistler 4045A50 and a thermocouple at the outlet of the propellant tank. Downstream of the propellant tank a flow measurement turbine was installed. Another pressure transducer STS TM212 and a

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thermocouple were located at the interface to the ignition demonstrator to record injection pressure and temperature. In the propellant supply no filter was used to prevent propellant crystallization or cavitation effects [13]. The propellants used were prepared and filtered in DLR's chemical laboratory. In case of tests with LMP-103S space grade propellant delivered from ECAPS AB was used. Data acquisition was done with a sampling rate of 1 kHz for the pressure and flow data and at a rate of 100 Hz for the temperatures. All ignition tests were recorded with a video camera and analyzed afterwards. Besides the propellant system the test position was equipped with an H_2O support line for flushing the thruster or the ignition demonstrator in case of emergency.

For pilot flame ignition tests the gaseous hydrogen and oxygen supply and the high voltage supply of the test bench were additionally used to drive the torch igniter. The torch igniter is a small pre-combustion chamber working with hydrogen and oxygen at pressures up to 40 bar. The torch was ignited with two conventional spark plugs. Afterwards the hot combustion gases were guided into the main combustion chamber of the ignition demonstrator creating a stable pilot flame into which the propellant was then injected or which preheated the chamber. Depending on the torch settings (mixture ratio and backpressures) thermal output powers above 20 kW were possible.

However, for the glow plug ignition tests the electrical test bench supply was used consisting of an adjustable direct current power supply. Glow plugs used for the tests were supplied with a maximum voltage of 11 V and a maximum current of 20 A.

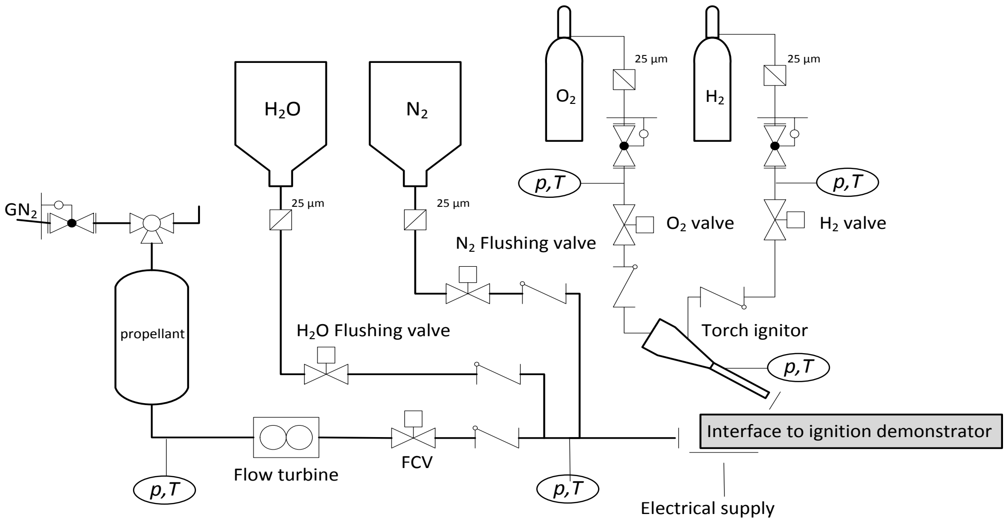

Figure 1: Schematic test bench setup with gas, fluid and electrical supplies

3.2. Ignition Demonstrators

For pilot flame and for glow plug ignition tests two different demonstrators were used and are further described in the following section. The tests conducted herein were preliminary ignition tests that should clarify the question if thermal ignition of ADN-based liquid monopropellants is feasible and which challenges are to manage.

Pilot Flame Ignition Demonstrator

Pilot flame ignition tests were done with an H_2/O_2-torch igniter that was flanged to the faceplate of the ignition demonstrator at an angle of 30 degrees from the centerline. For the presented tests the torch was operated at a mixture ratio of oxidizer to fuel (ROF) between 1.2 and 1.5 with hot gas output mass flows of around 2.5 g/s. The power of the torch therefore varied between 16 and 20 kW. While firing the torch its pressure and temperature were monitored and recorded. In the conducted tests the runtime of the torch was set constant to 1000 ms.

The pilot flame ignition demonstrator itself is shown in Figure 2 and was built up of a stainless steel cylindrical combustion chamber with 1" inner diameter and a length of 150 mm. Hence the pilot flame ignition demonstrator had a characteristic combustion chamber length of 1.53 m. A conical nozzle was used which had a throat diameter of

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8 mm and an expansion ratio of 5. The convergent part had an angle of 25 degrees, the divergent supersonic part an angle of 15 degrees. Injection of the propellant was done via a full-cone swirl injector with a spray angle of 85 degrees. This high spray angle in combination with the small chamber diameter should ensure high propellant-wall-interaction with superior heat transfer compared to interaction only between hot pilot flame gases and liquid propellant spray. Water evaporation inside the propellant should be improved. The ignition demonstrator was equipped with two pressure transducers type Kistler 4045A50, named "P-BK-01" and "P-BK-02", in the combustion chamber as well as two type K thermocouples measuring the combustion chamber temperatures near the injector and near the nozzle.

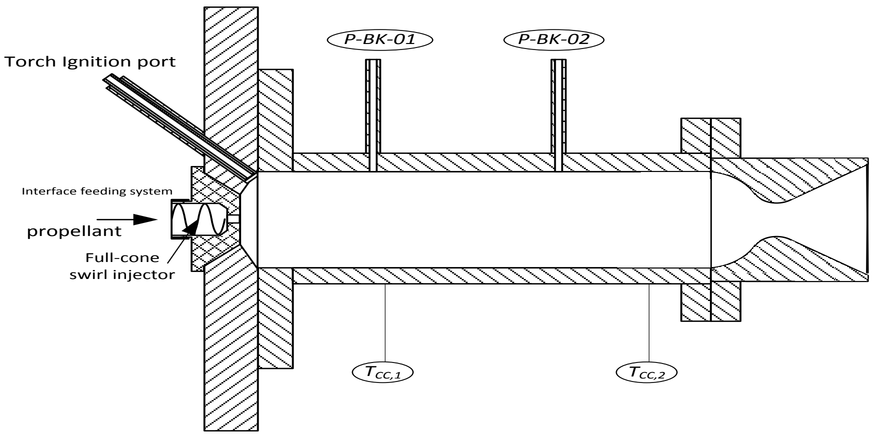

Figure 2: Drawing of pilot flame ignition demonstrator

Glow Plug Ignition Demonstrator

The glow plug ignition demonstrator was smaller in design than the pilot flame ignition demonstrator. It was designed for operation at mass flows between 1 and 5 g/s of propellant. The setup, shown in Figure 3, consisted of a conventional glow plug supplied with 11 V. The propellant was fed into a stainless steel housing with an annular flow channel. The glow plug reached a maximum steady-state temperature of about 900 °C. At the end of the glow plug a flame holding device was located to enlarge recirculation of hot combustion gases and enhance propellant decomposition and combustion. The glow plug ignition demonstrator was equipped with thermocouples measuring the temperatures at the injection port and near the flame holding device where the propellant should combust. Since no nozzle was used and combustion appeared at atmospheric pressure no pressure transducers were installed in the setup. The design of the glow plug ignition demonstrator partially resulted from gained knowledge throughout the pilot flame ignition tests. The pilot flame ignition demonstrator was originally designed for ignition and combustion research on ADN-based liquid monopropellants, especially for evaluation of thruster performance parameters. In contrast the glow plug ignition demonstrator was designed only for the investigation of the feasibility of thermal ignition via a glow plug. For data analysis the current and the voltage and temperatures at the inlet port and at the flame holding device were recorded during the tests. Additionally also these tests were filmed and the video data was analyzed.

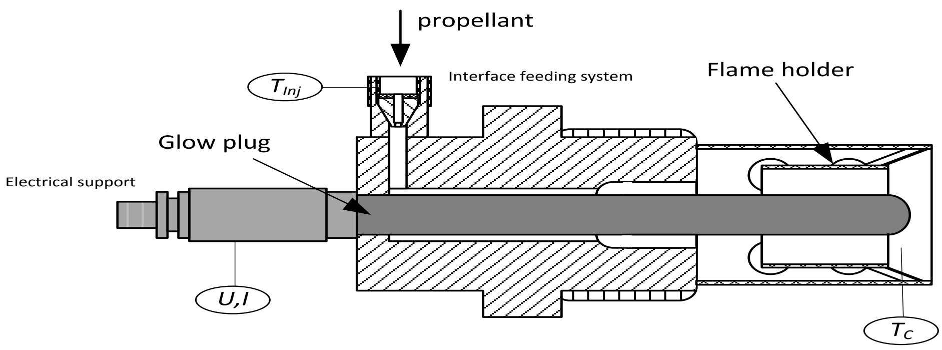

Figure 3: Drawing of glow plug ignition demonstrator

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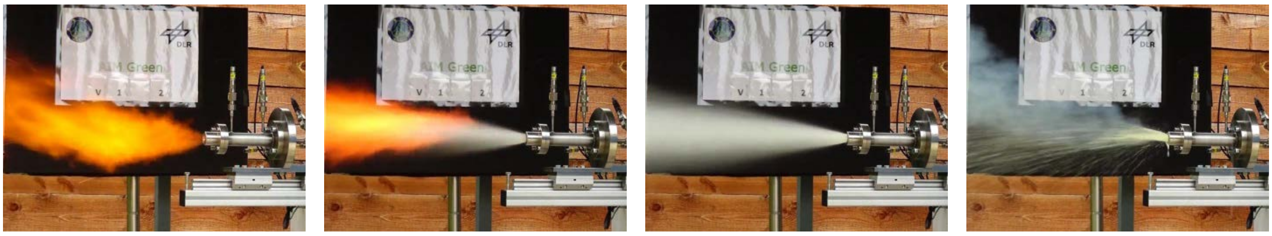
4. Results and Discussion

In this section the results of the ignition tests with ADN-based liquid monopropellants are presented and the significant details shown. Since during the majority of pilot flame ignition experiments FLP-106 and LMP-103S behaved similarly, only one propellant is presented exemplarily. When differences in propellant, ignition or combustion behavior were observed, this is mentioned and discussed in detail. In contrast to the pilot flame ignition tests during the glow plug ignition tests the propellant behavior altered drastically between FLP-106 and LMP-103S . This is as well discussed in detail below.

4.1. Pilot Flame Ignition

The first test with FLP-106 was conducted at a tank pressure of 26 bar, corresponding to a mass flow rate of 98 g/s. This is approximately the nominal mass flow rate for a 200 N thruster. In Figure 4 several frames from video data taken during this test are shown. In picture (a) a bright orange flame can be observed. This flame was the pilot flame created by the running H_2/O_2-torch igniter. The flame was still visible in picture (b), taken 120 ms after the FCV opened and injection of propellant into the combustion chamber had started. There is a slight color change which indicated partial propellant decomposition due to the heat-up in the pilot flame, but it is also observable that most of the propellant spray left the ignition demonstrator without decomposition. In the third picture (c) this gets even clearer. The torch igniter was still running but all of the propellant was leaving the chamber in liquid form. Picture (d) was taken when the FCV closed. At that moment the torch igniter was already shut off. Noticeable was the partial gasification of the propellant creating white smoke. Furthermore, the propellant spray turned more yellowish indicating a partial evaporation of water. After the test a yellowish wax-like residue was coating the nozzle. This phenomenon is shown in Figure 6. In Figure 5 the corresponding pressure traces are shown. The combustion chamber pressure transducers “P-BK-01” and “P-BK-02” showed no significant pressure increase which could indicate propellant decomposition or combustion. The slight increase in chamber pressure resulted from the firing torch igniter exhausting the hot pilot flame gases into the combustion chamber. This test was also conducted with LMP-103S without any noticeable changes. Video analysis indicates that for that amount of propellant the residual time in the combustion chamber in combination with the heat transfer from the pilot flame and the chamber walls to the propellant are insufficient to evaporate the water and start ADN decomposition or initiate stable combustion.



Torch igniter running; propellant FCV closed (a)	120 ms after FCV opening; torch igniter still running (b)	400 ms after FCV opening; torch igniter still running (c)	torch igniter off; FCV closing (d)

Figure 4: Pilot flame ignition test with FLP-106

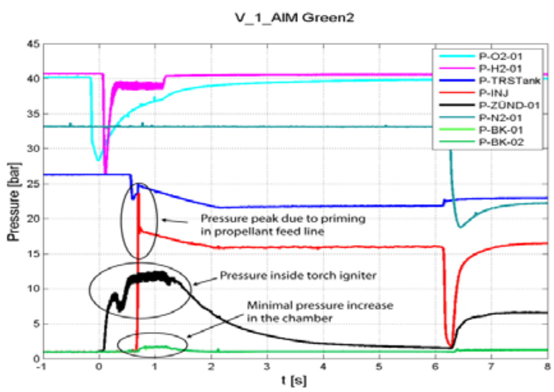


Figure 5: Pressure plot of pilot flame ignition test with FLP-106

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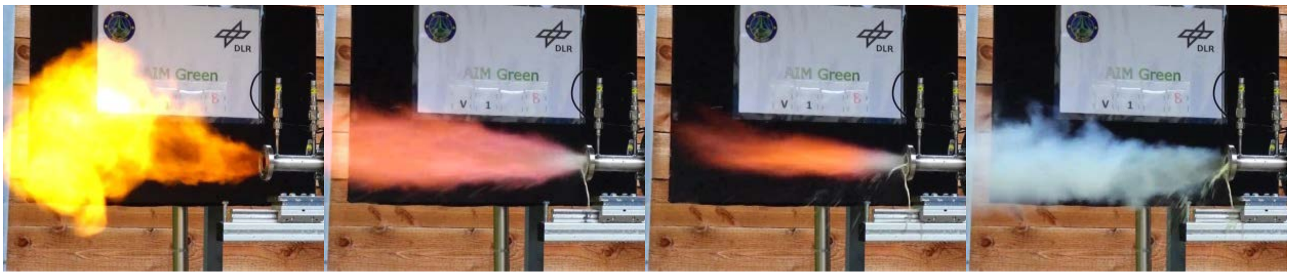
Figure 6: Propellant residue in nozzle after pilot flame ignition test

As a result of the first test the propellant mass flow rate was reduced by reducing the propellant tank pressure. This lead to a decreased amount of propellant injected into the combustion chamber and hence a reduced amount of energy should be needed to evaporate the water in the propellant and therefore enhance ignition. The second test was conducted with 4 bar tank pressure. The nozzle was removed for three reasons. Firstly, chamber pressure built-up was affecting combustion behavior but not the ignition process. Secondly, by removing the nozzle accumulation of propellant inside the chamber was prevented. The accumulated propellant could otherwise react spontaneously at local hot spots after the test. A third reason for the removal was obviating feedline instabilities which could occur at low feeding pressures with increasing chamber pressure.

Results of the second test are shown in Figure 7, pictures (a) to (d). Frame (a) shows the pilot flame from the running torch igniter 180 ms after ignition, like the one presented in the first test above. In the second picture (b) the propellant flow control valve was opened while the torch was on. Overlapping time between the pilot flame and the torch was 1000 ms. In contrast to the first test the resulting flame turned more reddish with a slight blueish change at the flame’s anchoring point. This flame remained stable until the torch igniter was shut off, seen in picture (c). Afterwards no further burning or reactions of propellant were observed. In the second and third picture a portion of the propellant still left the combustion chamber in liquid state and dripped of the edge of the chamber. Image (d) shows the propellant behavior after shutdown of the torch igniter. It was partially decomposing but neither igniting nor burning and most of it also left the ignition demonstrator in liquid state. Like in the test before, it is evident that the propellant composition changed due to a color change. A test with similar parameters and LMP-103S showed analog results.



Torch igniter after 180 ms	Torch igniter running; FCV opened; after 500 ms	torch igniter shut-off; FCV still open; after 1500 ms	Torch igniter off; FCV still open
(a)	(b)	(c)	(d)

Figure 7: Pilot flame ignition test with FLP-106 with reduced propellant mass flow

The third presented test was conducted with LMP-103S. In this test tank pressure was again increased to 17 bar but a smaller version of the full-cone swirl injector was installed to reduce propellant mass flow rate into the combustion chamber. The results of the previous tests indicated that heat exchange between pilot flame respectively combustion chamber walls and propellant spray was not sufficient to evaporate the water component in the propellant and to start decomposition. To increase pilot flame temperatures the oxygen supply line for the torch igniter was bypassed and flanged to the combustion chamber of the ignition demonstrator. Accordingly, the additional oxygen could burn at near-stoichiometric conditions (ROF 6) with the hot and fuel-rich torch exhaust gas inside the combustor. Additional

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oxygen was added to the pilot flame from 500 ms till torch shutdown. Propellant was injected 750 ms after the torch was ignited. In Figure 8 the pilot flame resulting from the torch igniter right after ignition can be seen in the video snapshot (a). The flame changed to a more stable and more blueish one when the valve for additional oxygen was opened and near-stoichiometric H_2/O_2-combustion with the pilot flame in the combustion chamber occurred, picture (b). In picture (c) the propellant FCV was opened and propellant injection began. In contrast to the other tests in this case a continuing combustion was observed and pressure transducers in the combustion chamber showed a pressure increase to 8 bar, Figure 9, with some occurring instabilities. The flame shown in image (c) turned even more blueish during burning time. Right after the additional oxygen valve was closed propellant combustion also extinguished. This is shown in the picture (d) of Figure 8. From that time on results again equaled the experiments presented before, the major part of the propellant left the ignition demonstrator unreacted in liquid state and no further reactions or pressure indications for propellant decomposition or burning were observed (pictures (d) and (e)).

Only torch running after 100 ms

(a)

Torch and additional oxygen added to combustion chamber; after 400 ms

(b)

Torch with additional oxygen and propellant FCV opened; after 800 ms

(c)

Torch and additional oxygen shutdown; propellant FCV still open

(d) **(e)**

Figure 8: Pilot flame ignition test with LMP-103S at near-stoichiometric (ROF 6) pilot flame combustion

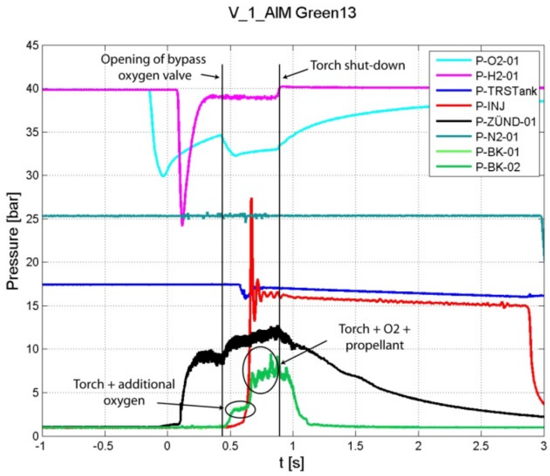

Figure 9: Pressure plot of pilot flame ignition test with near-stoichiometric (ROF 6) pilot flame combustion

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3.2. Glow Plug Ignition

The second investigated thermal ignition method was based on a glow plug ignition of the ADN-based liquid propellants. This ignition method is of great interest for multi-start operations like AOCS or RACS. The ignition demonstrator was designed for mass flows ranging from about 1-5 g/s of propellant. During the conduction of the pilot flame ignition tests it got obvious that liquid ADN-based monopropellants offer a long ignition delay due to water evaporation and even afterwards need a hot surface to sustain decomposition. An ignition via glow plug seemed suitable and an ignition demonstrator for preliminary tests was built. Since only the ignition process was investigated the demonstrator had no nozzle. For the conducted preliminary tests the glow plug was preheated before the FCV was opened. In the conducted test series the glow plug was preheated until it levelled out at approximately 900 °C, then FLP-106 or LMP-103S was injected by opening the FCV. During the campaign the tank pressure and therefore the injection mass flow was varied to find ignition limits. In the following section two tests, one for each of the propellants, is shown and illustrated.

Selected video snapshots (a) to (d) from the glow plug ignition test with FLP-106 are shown in Figure 10. In the first picture (a) the preheating phase of the glow plug can be seen. In picture (b) the FCV was opened and propellant started to react in the combustor. A visible yellowish flame directly occurred. The third and the fourth picture (frames (c) and (d)) show the stable reaction and combustion of propellant. Temperatures measured at the flame holding device of the ignition demonstrator increased shortly after opening the FCV from 900 °C to around 1250 °C, picture (c). This cannot be due to the resistive heating of the glow plug since the temperatures were above the maximum heating temperature of the plug as well as no increase in supply current was measured. It could be observed that besides the bright flame also a lot of white aerosol or smoke was generated, seen especially in (c) and (d). Combustion of the propellant was stable but the flame oscillated from time to time. This phenomenon can be observed when comparing the difference in flame structure between the picture (c) and (d).

Preheating glow plug (a) | Opening FCV (b) | FCV open (c) (d)

Figure 10: Preliminary glow plug ignition test with FLP-106

The same test procedure was repeated with LMP-103S instead of FLP-106. In Figure 11 the video analysis of that experiment is shown. In the first picture, image (a), the glow plug preheating is shown. After a steady state was reached and the supply current of the glow plug decreased, the propellant FCV was opened. Picture (b) shows the moment when the first propellant entered the combustor. At the beginning the flame looked bright yellowish but then turned nearly colorless as can be seen in the third, fourth and fifth image ((c), (d) and (e)). The flame was stable without oscillations, even a lot more stable than with FLP-106 in the test presented above, and increased in size which can be observed in the snapshots below. Compared to the FLP-106 tests no occurring smoke was observed but in contrast a lot of liquid propellant was dripping from the end of the glow plug ignition demonstrator, even at low tank pressures. When comparing the pictures (a) to (e) in series it can be recognized that the glow plug glowed orangeish in the preheating phase, afterwards when propellant injection started in (b) the luminosity dropped essentially due to the evaporation cooling caused from the water portion of the propellant and then increased again when combustion continued in (c). In picture (d) and (e) the luminosity of the glow plug was further rising, especially in picture (e) the radiation of the glowing plug was more intense than in the preheating phase (picture (a)). During preheating temperature reached a maximum heating temperature of around 900 °C. During the test temperatures increased beyond 1600 °C, the combustion temperature of LMP-103S, and finally lead to a burn through of the glow plug and of the thermocouple placed inside the flame. Therefore no maximum temperature can be given. During that time no supply current increase was recorded, so that temperature rise needs to be an effect of propellant combustion. It is supposed that no or little ADN decomposed but instead the methanol part of the propellant burned with the surrounding air. This is discussed in more detail later. Both ADN-based liquid monopropellants burned steadily in the glow plug ignition tests. When the propellant mass flow was increased

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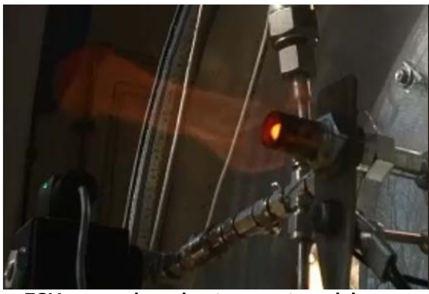
decomposition and combustion of the propellant continued but unreacted liquid parts dropped off the end of the glow plug ignition demonstrator.

Preheating glow plug
(a)

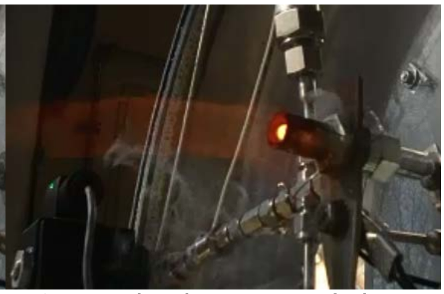
FCV opening
(b)

FCV open
(c)



FCV open; glow plug temperature rising

(d)



FCV open; glow plug temperature further rising
(e)

Figure 11: Preliminary glow plug ignition test with LMP-103S

3.3. Discussion of the Preliminary Thermal Ignition Test Results

The design of the pilot flame ignition demonstrator showed itself unsuitable for reaction initiation, ignition and stable and self-sustaining combustion at nominal mass flow rates for a 200 N engine. The demonstrator design was oriented at design considerations for other advanced liquid monopropellants under investigation at the propellants department of DLR Lampoldshausen. The conducted tests convincingly showed that ADN-based liquid monopropellants drastically differ in their reaction and combustion behavior compared to other liquid monopropellants. Major challenges were identified in heat transfer into the propellant. The energy amount provided by the pilot flame was high enough to theoretically evaporate the water in the propellant mixture and to initiate propellant decomposition and burning. Some partial reactions were initiated but with the pilot flame ignition demonstrator no sustained combustion could be reached. Furthermore when regarding the nozzle residues in the test with nominal mass flows it is observed that nearly all of the propellants water amount was evaporated. Since this happened when no or only little further energy by the pilot flame was supplied no decomposition and hence no combustion started and sustained. In fact the problem seems to be the delay caused by the time needed to evaporate the water portion of the propellant. Even when propellant mass flow was reduced the time for evaporation in combination with the given heat transfer due to the ignition demonstrator geometry was too poor to start reaction of the propellant. When the FCV was closed the residual propellant in the combustion chamber had time to be conditioned and to decompose, seen in the smoke generated afterwards.

Comparison of preliminary glow plug ignition tests and pilot flame ignition tests also support the fact that reducing propellant conditioning time, in other words the time for evaporating the water inside the propellant, is the key challenge. Energy input per propellant mass was approximately 100 times lower in glow plug ignition tests than in pilot flame ignition tests but there the propellant decomposed and ignited. Also a stable and sustained combustion was reached.

Tests underline that ADN-based liquid monopropellants have a two staged ignition process. In the first phase the propellant needs to be conditioned by energy supply to evaporate the water. This phase is depending on the heat transfer characteristics of the combustor. With enhanced heat transfer the delay time will decrease. In the presented pilot flame ignition tests that heat transfer process was not efficient enough to reach an ignitable propellant state inside the combustion chamber. After the propellant’s water component is evaporated decomposition and combustion can occur. Again here a second challenge was identified in the conducted tests. Once a portion of the propellant is conditioned and starts to release energy, the internal heat feedback in the propellant itself is insufficient to sustain combustion. Although the emitted chemical energy is high compared to the needed energy for water evaporation, the release time is too short to evaporate the water of a following portion of propellant. As a result an external heat-feedback mechanism is needed to sustain the decomposition of propellant. In the presented tests this reaction-holding device is the glow plug. In contrast to the pilot flame ignition demonstrator the glow plug can absorb and store heat to overcome conditioning delay of the propellant and still has a high enough temperature to initiate propellant decomposition and ignition. The glow plug not only fulfilled the task to evaporate the water in the propellant composition, it also provided to necessary ignition energy to the decomposed propellant species which could not be realized by the pilot flame alone.

Another point to mention is the different behavior of FLP-106 and LMP-103S. With FLP-106 no combustion initiation could be achieved by pilot flame ignition in any test. Ignition tests with LMP-103S seemed to succeed when the pilot flame was run at near-stoichiometric conditions. Video data analysis indicated that with LMP-103S no propellant combustion occurred in the pilot flame tests. Rather components of the propellant, namely methanol, combusted in combination with the additional oxygen inside the chamber. One indication is the blueish hydrocarbon flame that was observed not indicating combustion of ADN or other nitrogen species. Also the glow plug tests support that assumption. In the LMP-103S test the combustion temperature increased above the maximum combustion temperature of LMP-103S. In contrast with FLP-106 the measured temperature was 400 °C below the theoretical combustion temperature of the propellant. Also the flame showed no characteristic features of ADN-based liquid propellant combustion. Coinciding with the observed white smoke indicating of no complete reaction of ADN seems legit. Furthermore in case of LMP-103S testing a lot of liquid propellant was dripping of the edge of the ignition demonstrator even in tests with low tank pressures and therefore little mass flow rates. Anyway reaction initiation and ignition were satisfying and reliable. Furthermore the start-up phase until reaching steady state combustion could be achieved with the glow plug ignition demonstrator.

4. Summary

Preliminary tests on thermal ignition with ADN-based liquid monopropellants FLP-106 and LMP-103S have been conducted with two thermal ignition methods. The first thermal ignition method was based on a pilot flame igniter that could be of interest for operations where only a few ignitions are needed. The second investigated thermal ignition method was based on a glow plug ignition interesting for multi-start missions. Results of the test indicate that ADN-based propellants offer a different propellant behavior compared to conventional liquid monopropellants. At first the propellant needs to be conditioned by evaporating the water portion in the propellant. In this phase the heat transfer from the igniter into the propellant plays a major role affecting the main ignition delay time. After evaporating the water propellant decomposition can be initiated. It was found that an external heat feedback is necessary to sustain propellant decomposition and hence propellant combustion. While tests with a pilot flame igniter and a conventional cylindrical combustion chamber were not successful, ignition of ADN-based liquid monopropellants via a glow plug showed satisfying decomposition and ignition behavior despite the glow plug ignition demonstrator construction was originally designed for ignition of hydrocarbon propellants. With the conducted preliminary thermal ignition tests a profound knowledge could be gained concerning propellant and ignition behavior of FLP-106 and LMP-103S. Furthermore similarities and differences of both propellants could be analyzed and allow improvement of thermal ignition methods for future research.

5. Outlook

The conducted thermal ignition tests will be repeated under vacuum conditions in the near future when the corresponding test position is set up. Then effects distorting ADN-based liquid monopropellant ignition research, like in the presented tests with LMP-103S when methanol from the propellant burned with air, will be avoided. Furthermore ignition behavior could change due to vacuum effects like propellant flashing. Boiling of propellant components can in these cases aid or hinder decomposition and ignition of the multicomponent aqueous propellants. Secondly further research needs to be done to investigate the characteristic ignition behavior of ADN-based liquid monopropellants. Especially heat transfer in the conditioning stage needs to be understood in more detail since this part of ignition is the most energy and time consuming process. Furthermore for both ignition demonstrators optimization work needs to be done. The pilot flame ignition demonstrator so far used was designed wrong and

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needs to be improved concerning heat transfer, external reaction stabilization and heat feedback. This could possibly be realized by using a hot surface inside the combustion chamber or porous materials. The design of the glow plug ignition demonstrator, though it was not optimized, worked well but needs to be improved and expanded to investigate detailed ignition effects and influences resulting from combustion chamber pressures. Further investigation for both ignition methods needs to be conducted to find out minimum energies for propellant conditioning and initiation and at the best a separated two-staged ignition method can be found to efficiently and fast evaporate the water and then initiate propellant decomposition and combustion while the igniter can maintain the high combustion temperature.

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References

[1] E. E. C. Agency, *"Agreement of the Member State Committee on the Identification of Hydrazine as a Substance of Very High Concern."*, 2006.

[2] Y. Ide, T. Takahashi, K. Iwai, K. Nozoe, H. Habu und S. Tokudome, „Potential of ADN-based Ionic Liquid Propellant for Spacecraft Propulsion," Asia-Pacific International Symposium on Aerospace Technology, 2014.

[3] K. Anflo, T. A. Grönland, G. Bergman, M. Johansson und R. Nedar, „Towards Green Propulsion for Spacecraft with ADN-Based Monopropellants," Indianapolis, 2002.

[4] T. Katsumi, H. Kodama, T. Matsuo, H. Ogawa, N. Tsuboi und K. Hori, „Combustion Characteristics of a Hydroxylammonium Nitrate Based Liquid Propellant. Combustion Mechanism and Application to Thrusters," in *Combustion, Explosion, and Shock Waves, Vol. 45, No. 4*, 2009.

[5] L. Werling , N. Perakis, S. Müller und S. Schlechtriem, „Hot firing of a N2O/C2H4 premixed green propellant: First combustion tests and results," in *Conference: Space Propulsion Conference*, Rome, 2016.

[6] M. Negri, „Replacement of Hydrazine: Overview and First Results of the H2020 Project Rheform," in *6TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS)*, Rom, 2015.

[7] J. Hall, Advances in Spacecraft Technologies, Rijeka: InTech, 2011.

[8] N. Wingborg, C. Eldsäter und H. Skifs, „Formulation and Characterization of ADN-Based Liquid Monopropellants," Cagliari, 2004.

[9] K. Anflo und R. Möllerberg, „Flight demonstration of new thruster and green propellants technology on the PRISMA satellite," 2009.

[10] N. Wingborg, A. Larsson, M. Elfsberg und P. Appelgren, „Characterization and Ignition of ADN-Based Liquid Monopropellants," Tucson, 2005.

[11] N. Wingborg, M. Johansson und L. Bodin, „Initial development of a laboratory rocket thruster for ADN-based liquid monopropellants," Tumba, 2006.

[12] D. Amariei, L. Courthéoux, S. Rossignol, Y. Batonneau, C. Kappenstein, M. Ford und N. Pillet, „Influence of the fuel on the thermal and catalytic decompositions of ionic liquid monopropellants," Tucson, Arizona, 2005.

[13] C. Kappenstein, Y. Batonneau, E.-A. Perianu und N. Wingborg, „Non Toxic Ionic Liquids as Hydrazine Substitutes. Comparison of Physico-Chemical Properties and Evaluation of ADN and HAN," Cagliari, 2004.

[14] K. Neff, P. King, K. Anflo und R. Möllerberg, „High Performance Green Propellant for Satellite Applications," Denver, 2009.