IGNITION OF ADN-BASED MONOPROPELLANTS – RESULTS OF THE EUROPEAN PROJECT RHEFORM

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Abstract

Goal of the project RHEFORM is to develop new technologies for propulsion systems that use liquid monopropellants based on ammonium dinitramide (ADN). The aim is to enable the replacement of hydrazine with green propellants. Thus future systems will be less extensive to handle, will be more sustainable and better suited for complex missions. The present work provides a short overview of the RHEFORM project. The focus is on the results obtained by catalytic as well as thermal ignition of ADN-based liquid monopropellants FLP-106 and LMP-103S.

Nomenclature

A_t Throat area   m²
L^* Characteristic combustion chamber length   m
V_c Combustion chamber volume   m³

1. Introduction

Since the 1960s the standard monopropellant for spacecraft propulsion systems has been hydrazine. The associated technological heritage is extremely large. On the other hand hydrazine has severe disadvantages: it is toxic and carcinogenic, thus increasing the complexity of transportation, handling, fuelling and testing. The life-cycle of hydrazine propulsion systems are therefore costly. New regulations could restrict the use of hydrazine: in 2011 it was included in the candidate list of substances of very high concern by European Union under the Registration Evaluation Authorisation and Restriction of Chemicals (REACH) law.

Research activities are conducted worldwide to develop a suitable alternative for hydrazine. Liquid propellant blends based on ammonium dinitramide ($NH_4N(NO_2)_2$) are considered as promising replacements. An advantage compared to hydrazine is the easier transportation. For instance LMP-103S, the ADN based monopropellant with the highest degree of maturity, can be air-shipped. Liquid ADN-based propellants are easier to handle and fuel at the launch site: the fuelling of LMP-103S requires on third of the man-hours in comparison to hydrazine fuelling [1]. The less restrictive handling procedure made it possible to get approval for LMP-103S handling at different launch

sites. Consequently, systems based on ADN were launched from 3 different continents in 2016.

Additionally, ADN-based monopropellants have a higher performances compared to hydrazine. The specific as well as the volumetric specific impulse are higher than hydrazine. During the PRISMA mission a direct comparison between a hydrazine thruster and a LMP-103S thruster was conducted: the specific impulse was 6 to 12 % higher and the volumetric impulse 31 % than with hydrazine [2].

Some limitations are associated with ADN-based monopropellants propulsion systems. The combustion temperature of LMP-103S is 1630 °C which is much higher than the one for hydrazine which is around 900 °C. In order to withstand the higher temperatures, ITAR regulated materials have to be used for the chamber wall. A reduction of the combustion temperature would enable the use of platinum alloys, the material used for hydrazine thrusters. If feasible, the same combustion chamber could be used. The possibility of reducing the combustion temperature by increasing the water content in the propellant has been studied in the project RHEFORM. The results have been presented in [3]. A second limitation of current ADN-based thrusters is their lack of cold start capability. So far ADN-based thrusters are ignited via a preheated catalyst. The catalyst used for LMP-103S must be pre-heated to 350 °C. The propellant does not ignite reliably if the catalyst temperature is below this temperature. In contrast hydrazine systems allow cold starts i.e., ignition without preheating the catalyst. Nevertheless, preheating is often used in hydrazine thrusters in order to extend the life of the catalyst.

2. The RHEFORM project

RHEFORM is a project funded by the Europeans Union Horizon 2020 program. The name RHEFORM is an acronym for: "Replacement of hydrazine for orbital and launcher propulsion systems". The project runs from January 2015 to the end of 2017. The RHEFORM consortium comprises 9 entities from 4 European countries: Austria, France, Germany and Sweden. Two universities are involved: the University of Poitiers (UP and the University of Applied Sciences Wiener Neustadt (FHWN). Three research centres are participating to the project: the German Aerospace Center (DLR), the Swedish Defence Research Agency (FOI), and the French National Center for Scientific Research (CNRS). Two companies are involved: Lithoz GmbH and FOTEC GmbH. Two space companies are participating: ECAPS and Airbus Safran Launcher (ASL).

Fig. 1. RHEFORM partners

The following main activities are addressed in RHEFORM:
- Selection of two reference cases. A market analysis was conducted to select the thruster classes with the highest market volume. Based on the analysis two classes were selected: 20 and 200 N. The typical application of the 20 N thrusters is for Attitude and Orbit Control Systems (AOCS) for spacecrafts. The application of the 200 N thrusters is Roll and Attitude Control System (RACS) for launcher and deorbiting. Based on these applications the requirements on the propulsion system and on the propellant have been defined.
- Variations on existing propellants (LMP-103S and FLP-106). Calculation of amounts of water required to obtain combustion temperatures compatible with selected wall materials. The possibility of reducing the combustion temperature by increasing the water content in the propellant has been studied. The results have been presented in [3]. Experimental characterization of the propellant variations.
- Development and testing of granulated and monolithic catalysts, aiming at reducing the pre-heating temperature.
- Development and testing of thermal igniters.
- Implementation of ignition methods in two thruster demonstrators. Once that the ignition system will be developed, they will be implemented in two thruster demonstrators. This activity will take place in the last year of the project.

The present paper will be focused on catalyst and thermal igniter development.

3. Catalyst development

As mentioned in the introduction, one of the drawbacks of the existing propulsion system based on LMP-103S is the necessity to pre-heat the catalyst to temperatures of approximately 350 °C.

In RHEFORM new catalysts are considered trying to reduce the preheating temperature. Two types of

catalyst supports, granulated and monolithic supports, are investigated. For granulated catalyst support different shapes are included, for example spheres, beads, pellets, and extrudates. A significant application of granulated catalysts is hydrazine thrusters. Monolithic supports differ from granulated ones because the support is made of a single, monolithic, structure with channels in which the propellant flows. Conventionally, monoliths are produced via extrusion. Although monoliths are typically used in the automotive industry, their use for space applications could be interesting due to better structural stability, better control of the active surface area and lower pressure losses.

3.1   Granulated catalyst development
The first step in the development of a granulated catalyst is the selection of a support material. Both, the geometry and the material of the support influence the behaviour of the catalyst.

3.1.1   Geometry of granulated supports
The catalyst used in propulsion applications should be as compact as possible. Therefore, the aspect ratio giving the highest packing density was selected. It was shown in experimental investigations presented by other researcher groups such as [4] that the ratio for cylinders is 1.2.

An important parameter connected with the geometry of the support is the local void fraction, the ratio of the volume of the voids over the total volume of the area considered. This parameter influences the drop losses: areas of the catalyst with high void fraction will have lower pressure drops. This leads to the formation of preferential paths. The distribution of the propellant in the catalyst should be as uniform as possible. Consequently, preferential paths should be minimized, i.e. the local void fraction should remain as uniform as possible across the catalyst bed.

A complete uniformity of the local void fraction is not possible due to the influence of the catalyst bed wall. The wall has an ordering effect, particularly on the particles close to it. This effect is influenced by the support shape and size. Based on previous theoretical works, a model was implemented to simulate the local void distribution in a catalyst bed. The results showed that a more uniform distribution of local voids is obtained with cylindrical rather than spherical particles. The ratio of the diameter of the catalyst bed to that of the particles plays also an important role. For small values of the diameter ratio the void distribution is not at all uniform with a large area near the wall with lots of voids. The distribution becomes more uniform increasing the diameter ratio. Above a diameter ratio of 8 the changes in the distribution become marginal.

The diameter ratio influences also the mean void fraction of the complete catalyst bed. Small values of the ratio will lead to large mean void fractions. For cylindrical granules the model indicated that the variations of mean void fraction becomes negligible for diameter ratios larger than 10. A smaller mean void fraction leads to a more compact catalyst bed, but also to a higher pressure drop. It can be seen that the selection of granulated supports is a trade-off between different aspects. Therefore, a precise value for the diameter ratio is subject of further (experimental) investigation.

3.1.2   Material of Granulated Supports
The choice of support material is based on considerations on their resistance and specific surface area. Support materials have to be extremely resistant: they are subjected to strong thermal shocks and are in contact with reactive gases at extreme temperatures. They should have a high specific surface area, because this increases the surface of contact between the propellant and the active phase. Moreover, the specific surface area should remain large for the entire life of the catalyst. Based on these requirements, different materials have been considered in RHEFORM. Two of the materials selected were commercially available: gamma alumina (γ-Al_2O_3), and yttria stabilized zirconia (YSZ). Three other materials were synthetized: silicon-doped alumina and two types of hexaaluminates, namely "hexaaluminate A" ($LaAl_{11}O_{18}$) and "hexaaluminate B" ($BaAl_{12}O_{19}$).

These support materials were characterized. In order to simulate the effect of the combustion on the catalyst, the catalysts were subjected to heat treatment in air before the analysis, as listed in Table 1. X-ray diffraction (XRD) allowed the analysis of the nature of the crystalline phases. Other important information on the support as specific surface area, pore volume and pore size were determined by nitrogen sorptiometry.

The heat treatment allowed performing a preliminary selection of support materials. The material YSZ underwent substantial shrinkage after the heat treatment, and was therefore discarded. The specific surface area of the material hexaaluminate A was strongly reduced after the heat treatment and therefore this material was discarded as well.

Table 1. Specific surface area, pore volume, and pore size of selected support materials after heat treatment in air at different temperatures

Materials, Shape	Thermal treatment	m²/g*	cm³/g[†]	Å[‡]
DUS 1, Powder	(1200 °C – 4 h)	92	0.247	82
Hexaaluminate A, Powder	(1500 °C – 4 h)	7	0.018	118
Hexaaluminate B, Powder	(1500 °C – 4 h)	46	0.063	64
YSZ, Pellets	(1500 °C – 4 h)	< 0.1	-	-

* Specific surface area

[†] Pore volume

[‡] Pore size

3.1.3 *Catalyst active phase*

The second phase in developing a granulated catalyst is the selection of an active phase. In RHEFORM numerous active phases were tested. The deposition of the active phase is carried out by impregnating the granules with a solution of the active phase precursor at room temperature. The solvent is then removed by gentle evaporation at moderate temperature. Catalysts are obtained subsequently to an appropriate heat treatment of the solid thus obtained. The search for the optimal nature and percentage of active phases is still ongoing, and more details will be published in a future work.

3.2 *Monolithic Catalyst Development*

A monolithic catalyst is typically made of a support structure, a washcoat layer deposited on the support in order to increase the microscopic surface area and an active phase which is deposited on the washcoat layer.

Monolithic catalytic supports are typically produced via extrusion. With this technique only straight channels can be manufactured. In the RHEFORM project a novel 3D printing technique was implemented, called Lithography-based Ceramic Manufacturing (LCM) developed by the project partner Lithoz [5]. This method allows the fabrications of complex support geometries. It is based on the use of photocurable suspensions which can be crosslinked when exposed to light. The parts are manufactured layer by layer. The shape of the layer printed is controlled by the shape of the light beam. The parts direct after the printing process are called "green parts". The green parts need to be cleaned after printing and the organic matrix has to be removed in the so called "debinding"-step. Finally, the ceramic particles are sintered together in a furnace at high temperature.
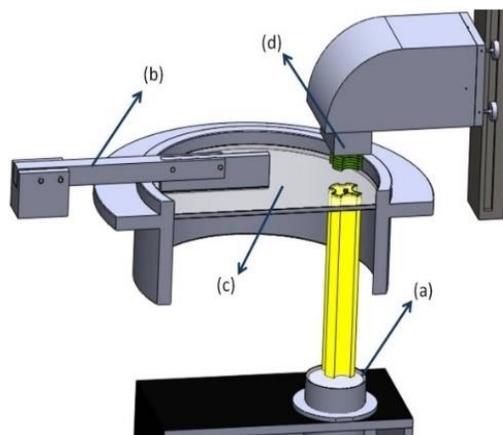

Fig. 2. Schematic principle of the LCM process: (a) Light source, (b) Coating knife, (c) Vat filled with resin and (d) Building platform, based on [6]

Three different designs were chosen for the printed monoliths, as shown in Fig. 3. The first design was based on triangular straight channels. Such design allowed was also manufactured by extrusion, allowing a comparison between the monoliths produced with two different processes.

The other two designs have complex 3D structure and can be manufactured only by printing.

The so called 'cellular' structure was selected to maximize the macroporosity of the design. The design was named 'polyhedral' structure. It is based on a basic repetition unit, in this case is a polyhedron with 26 faces. The basic idea with such a structure is the increase of the surface area inside the catalyst.
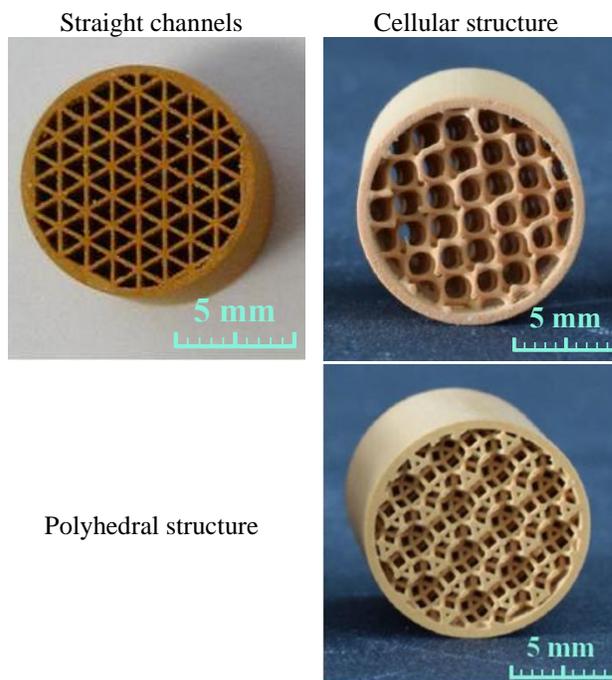

Fig. 3. Design of monolithic supports

For the manufacturing of monoliths 4 different ceramic materials are being evaluated, cordierite ($(Mg,Fe)_2Al_4Si_5O_{18}$, alumina), aluminium oxide (Al_2O_3, alumina), magnesium oxide (MgO, magnesia) and silicon nitride (Si_3N_4).

Stable and photocurable ceramic of all tested ceramic powders suspensions were prepared. These suspensions could be processed using Lithoz' LCM technology to print 3D green parts. Upon exposure to elevated temperatures the photopolymer was burned off and the ceramic particles were sintered together to create the final ceramic parts.

Characterisation of the samples in terms of their dimensional accuracy and precision was primarily done by conducting light microscopy. Exemplary picture material for 3D monolithic designs made from Cordierite 1 is depicted in Fig. 4.
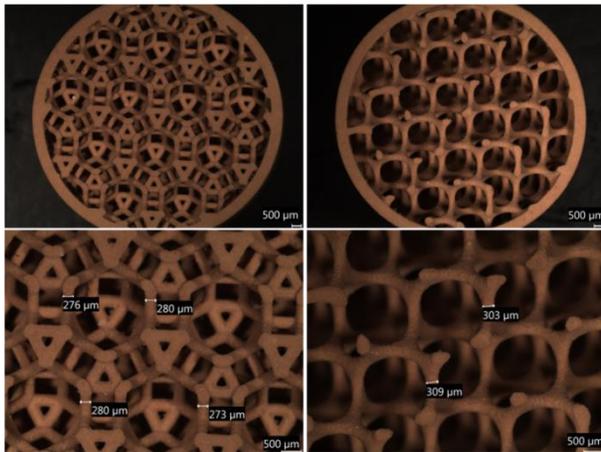

Fig. 4. Photographs of a polyhedral structure (left) and of a cellular structure (right) obtained after printing and sintering of a cordierite 1 sample

The measured data deviated slightly from the target geometry from the CAD due to two main reasons. One was the pixel array that was used to expose each layer of the monolith. Since the lateral dimension of each pixel is $40 \times 40\,\mu m$, very fine elements are approximated by manifolds of 40 µm. The other reason was light scattering by ceramic particles; since this phenomenon varies from material to material depending upon its refractive index, it cannot be completely compensated. Furthermore, since this effect only becomes discernible at the interfaces between cured and uncured material. It is relatively more pronounced for very fine elements such as the struts of the 3D designs or the walls of the linear monoliths.

In order to increase the microposorosity, i.e. increase the specific surface area, a washcoating layer was applied on the 3D printed supports. Washcoatings were applied dipping the supports in colloidal solutions of aluminium, alumina and or aluminium oxohydroxide

named sol AU and sol DUS. The excess material is then gently blown. The parts are then dried at room temperature and calcined in a muffle furnace. Several parameters influence the final layer and must be controlled: the temperature, the viscosity of the washcoating suspension, the duration of the procedure, and the drying conditions.

The active phase was deposited only once the washcoating of the different monolithic materials was shown as feasible. The deposition of the active phase is carried out by impregnating the washcoated monoliths with a solution of the active phase precursor at room temperature. The solvent is then removed by gentle evaporation at moderate temperature. The activation procedure is a critical step and depends on the nature of the active phase. The activation is conducted at higher temperatures, under oxygen and/or hydrogen, depending on the nature of the targeted active phase.

4. Thermal ignition of ADN-based monopropellants

A focus of the RHEFORM project is the reduction of pre-heating time of monopropellant thrusters, to make the igntion more prompt. This is crucial for emergency starts. A reduction of the pre-heating time can be achieved through a thermal igniter which can provide a high power input. Therefore, the suitability of thermal igniter for ADN-based propellants is investigated in RHEFORM. In this work the results obtained with a gaseous hydrogen (H_2)/oxygen (O_2) torch igniter are presented. Such an igniter is extremely flexible. By changing the amount of hydrogen and oxygen it is possible to change the amount of power delivered as well as the temperature of the combustion gases generated (ratio of oxidizer and fuel; ROF). It can deliver a considerable amount of thermal power. The model used for the ignition tests in the present work could deliver above 20 kW. It allows a large number of restarts which is particularly interesting while testing. It should be noted that the goal of the tests with the torch igniter is to verify if thermal ignition and sustained combustion can be achieved with a thermal ignition system. In an actual application the torch could be substituted with a pyrotechnic igniter reducing the complexity and weight of the ignition system.

4.1 Experimental Setup

A schematic drawing of the setup used for the ignition tests with a torch igniter is shown in Fig. 5. As combustion chamber a cylindrical 1 in stainless steel tube was selected. The internal diameter is 25.6 mm. The length was 150 mm. This results in a characteristic length L^* of:

$$L^* = \frac{V_c}{A_t} = 1.53 \text{ m} \qquad (1)$$

In previous tests conducted at DLR with another green monopropellant, a characteristic length of 1.5 offered best combustion performance. The nozzle throat diameter (8 mm) was selected to have a chamber pressure of 20 bar for a propellant mass flow rate of 100 g/s. The geometry of the nozzle was based on the experience at DLR with testing at ambient conditions. A conical nozzle with a rounded throat and an expansion ratio of 5 was designed. An angle of 25° for the convergent and of 15° for the divergent nozzle section was selected. The expansion ratio of 5 was small enough to assure that no flow separation takes place, but it provides a more clean flow than a truncated nozzle. Commercial full-cone swirl injectors from Spraying System Co. were used. In the tests conducted with FLP-106 two different injector sizes were used: size 3 and size 2. The two injectors had similar geometries, but the former had a smaller cross-sectional area, and therefore provided a smaller mass flow rate with the same tank pressure. The tests with LMP-103S were conducted with a swirl injector size 1. A regulated supply of hydrogen, oxygen and nitrogen was available at the test bench. The setup offered the possibility to flush the injector and the combustion chamber with water or nitrogen. The mixture ratio (ROF) and power output of the torch igniter could be modified by changing the feeding pressure of hydrogen and oxygen and the diameter of the sonic orifices placed in the igniter's feeding lines.
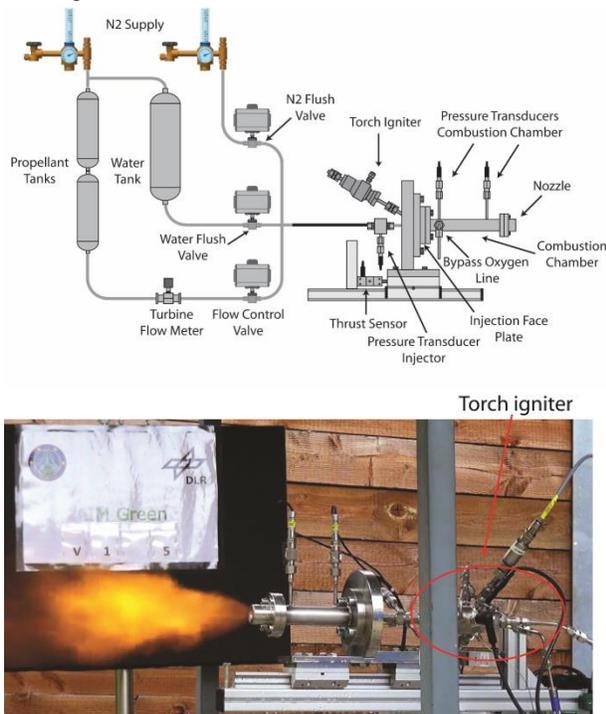

Fig. 5. [Top] Schematic drawing of ignition demonstrator. [Bottom] Ignition demonstrator with torch igniter

4.2   Results obtained with reference chamber

The results of the tests conducted with the cylindrical combustion chamber, without flame (reaction) holding devices are described in this section. The configuration of the torch igniter was kept constant during the tests. The mass ratio of oxidizer to fuel (ROF) was around 1.2 to 1.5 and the power output ranged from 16 to 20 kW. The torch was fired for 1000 ms. Tests were conducted with different tank pressures from 2 to 26 bar. Depending on the tank pressure, the mass flow rates of the propellant injected varied from below 30 g/s to 100 g/s. During the tests with the lowest tank pressure (2 and 4 bar) the exit nozzle of the combustion chamber was removed to avoid the formation of a back pressure in the combustion chamber and hence feedline instabilities. The FCV opened when the torch was ignited (the delay between torch ignition and FCV opening was varied between 100 and 900 ms) and closed 3000 ms later. Frames of one of the tests conducted with the reference chamber are shown in Fig. 6. The results of the other tests were similar. The power of the torch was sufficient to vaporize the propellant in all the conducted tests. The chamber cooled rapidly due to liquid propellant evaporation after the torch shutdown. 1000 ms after the torch was shut down a considerable amount of propellant left the chamber in liquid form. No clear ignition was observed in the test. In tests conducted with a nozzle the pressure in the combustion chamber remained below 2 bar, with the exception of one test during which several pressure spikes were observed.

| 180 ms after ignition | 960 ms after ignition: Start of propellant injection |

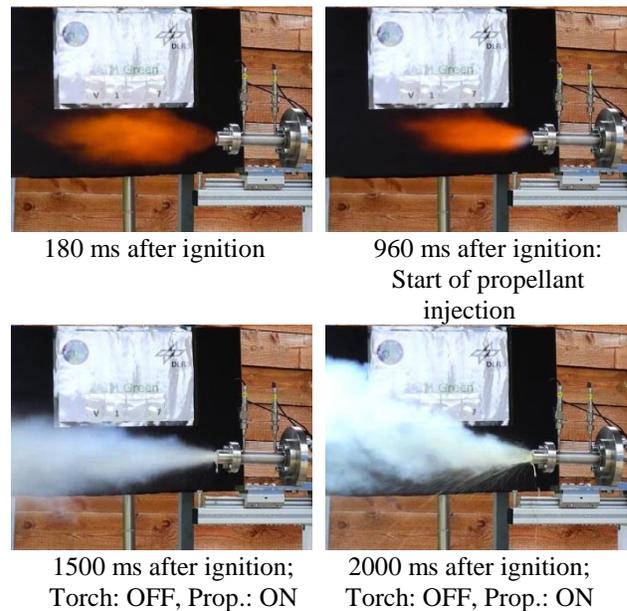| 1500 ms after ignition; Torch: OFF, Prop.: ON | 2000 ms after ignition; Torch: OFF, Prop.: ON |

Fig. 6. Selected video frames of an ignition tests with the torch igniter and the reference chamber

In the tests conducted without a nozzle, vaporization of the propellant was observed. Combustion took place outside the chamber, possibly reacting with atmospheric oxygen. In a test conducted with the lowest tank pressure (2.0 bar), the flame was much brighter than in the previous tests, likely due to decomposition of ADN.

In the last test additional oxygen was added directly in the combustion chamber to facilitate ignition. The torch was working with a ROF of around 1, the amount of additional oxygen was selected in order to have an ROF of 6 in the combustion chamber.

Combustion was observed when the torch and the additional oxygen were still running with the pressure in the combustion chamber rising to 7 bar. A video snapshot of this is shown in Fig. 7. It is not clear if ADN decomposed, but the additional oxygen has probably reacted with the fuel (methanol) contained in the propellant LMP-103S.

Fig. 7. Video snapshot of the ignition test with the torch igniter and additional oxygen

4.3 Tests with modified chamber

A hypothesis to explain the inability to ignite the propellant using the basic configuration was formulated: the necessity to have some thermally distributed support to facilitate the vaporization of the propellant and the decomposition of ADN. In order to verify this hypothesis the ignition demonstrator was modified. Two setups, called "Porous-A" and "Porous-B", were tested.

4.3.1 Setup Porous-A

The setup A was the first modification of the basic demonstrator. A schematic drawing is shown in Fig. 8.

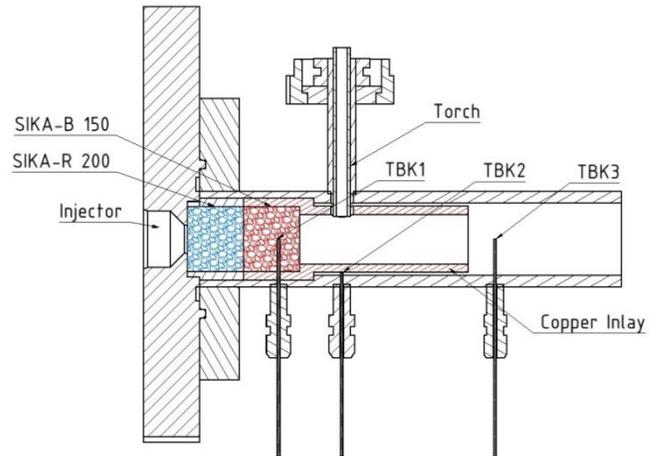A copper inlay and two porous discs were added in the chamber.

Fig. 8. Setup Porous-A. TBK1, 2, 3 are thermocouples

A goal of the first porous material (SIKA-R 200 stainless steel) was to achieve a more uniform distribution of the propellant. A limited temperature increase of the first inlay from the torch was expected, due to the low thermal conductivity of stainless steel and the fact that the hot gases from the torch do not pass the material. The second porous material (Sika-B 150 bronze) was designed to be preheated by the torch, mainly by heat coming from the copper inlay. The heated porous material should vaporise the propellant and act as reaction holding device. The good thermal conductivity of the porous material in combination with the copper inlay should facilitate the heat feedback from the reaction zone backwards into the liquid propellant. The torch igniter was placed perpendicular to the chamber to heat the copper inlay and the SIKA-B 150 porous material. A microshowerhead injector, fabricated by ASL, was used. The combustion chamber was equipped with three thermocouples. One (TBK1) in the middle of the bronze porous material, the second (TBK2) placed on the outer side of the bronze inlay, opposite to the torch and the third (TBK3) in the middle of the chamber. The firing time of the torch igniter was limited to not overheat the parts directly in contact with the torches' exhaust gases, in particular the flame tube connecting the igniter to the combustion chamber. With the configuration used with setup porous-A a maximum firing time of 3 seconds was possible.

Preliminary igniter tests were conducted. A single firing of the igniter did not heat the porous material sufficient. For this reason the hot firing tests were conducted according to the following sequence: torch firing 3 s, pause 40 s, torch firing 2.5 s, torch firing and FCV open 0.5 s.

The test setup did not allow measuring the mass flow rate, being below the sensitivity of the sensor used. Cold flow tests were conducted with tank pressure of 7 bar and FCV opening time of 500 ms (same condition as in the hot fire test) using water. The water was

collected and weighted. The amount of water in the 3 tests conducted was 5.7 g. All the subsequent tests were conducted with the same tank pressure and FCV opening time.

Using the sequence described above, tests were conducted both with water and LMP-103S. The results of two representative tests are shown in Fig. 9. In *test 024*, conducted with water as propellant simuli, the temperature in the porous material (TBK1) and in the chamber (TBK3) decreases suddenly after the injection of water. In test 028, conducted with LMP-103S, a similar behaviour was observed directly after the opening of the FCV. The propellant vaporised upon injection. Corresponding to the injection of propellant a sudden decrease of combustion chamber temperature (TBK1, TBK3) was observed. For some seconds after the propellant injection a noticeable amount of brown smoke came out of the chamber. Associated was an increase of the temperature in the chamber (TBK3) and with some delay in the porous material (TBK1). No flame was observed. Probably only a partial decomposition of ADN took place, so explaining the increase in temperature.
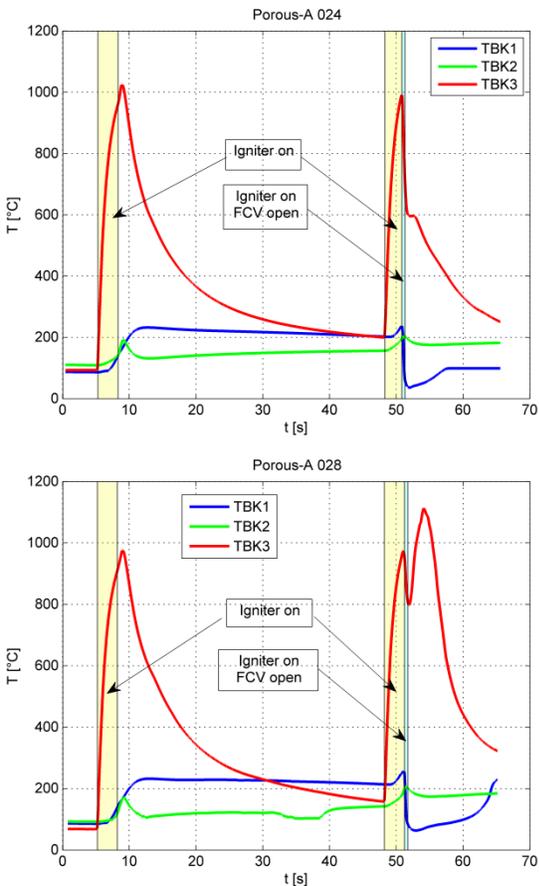

Fig. 9. Results of two tests conducted with the setup Porous-A. Injected fluid: [Top] water; [Bottom] LMP-103S

Similar results were obtained in the other tests conducted with setup Porous-A and LMP-103S. No flame was observed. The formation of brown smoke for some seconds after the propellant injection was observed as well. Possibly a partial decomposition of ADN took place, explaining the increase in temperature.

The conclusion being that the energy of the torch igniter and the thermal energy accumulated in the porous material were not sufficient to cause a direct ignition of the propellant. Nevertheless the propellant left in the chamber after the closure of the FCV did decompose to some degree, leading to heat release and the production of smoke.

4.3.2 Setup Porous-B

The setup Porous-B was a modification to the setup Porous-A. A schematic draft of the setup is given in Fig. 10. In the setup two porous materials were used: SIKA B-200 (indicated in blue) and SIKA B-150. Both were made of sintered bronze. This material has a good thermal conductivity; consequently the temperature distribution in the inlay should be close to uniformity. The position of the torch igniter was changed with respect to setup Porous-A: the torch was mounted on the face plate. In this setup the combustion products of the torch must flow through both porous inlays. The advantage of this setup is that both inlays material are heated substantially from the torch. The power of the torch had to be reduced to avoid melting the porous inlay.

The testing sequences for the setup Porous-B were similar to those used for the setup Porous-A with two torch firing separated by a pause. Several tests were conducted increasing stepwise the firing time of the torch to determine the time necessary for ignition of the propellant.
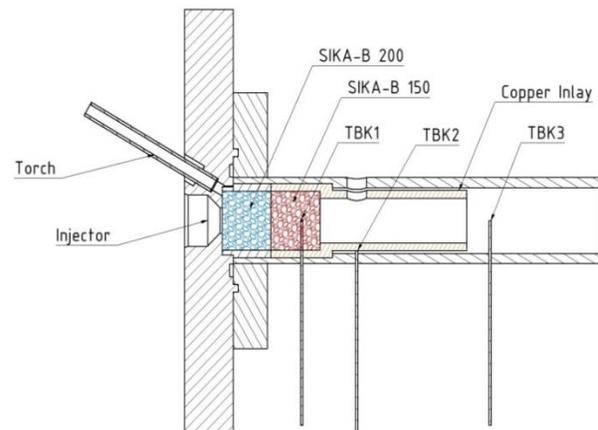

Fig. 10. Setup Porous-B

A clear ignition was obtained for torch firing time above 6 s. For example the results of a representative test (Porous-B 085) are shown in Fig. 11. In this test the

following sequence was used: torch firing 7 s, pause 40 s, torch firing 7 s, torch firing and FCV open 1 s.

During the firing of the torch without injection of propellant a considerable amount of white smoke came out of the chamber. This was probably water vapour generated from the torch igniter. In correspondence with propellant injection no visible flame was detectable. When the FCV was opened, an increase in temperature was measured by all three thermocouples, in particular by the sensor TBK1 (placed in the porous material). After closing the FCV a green flame surrounded the combustion chamber. Subsequently, a very bright green flame anchored in the chamber. A dramatic increase of the temperature in the chamber (TBK3) was measured accordingly. A maximum temperature of 900 °C was measured. In another tests with the same sequence a temperature of 1200 °C was measured.
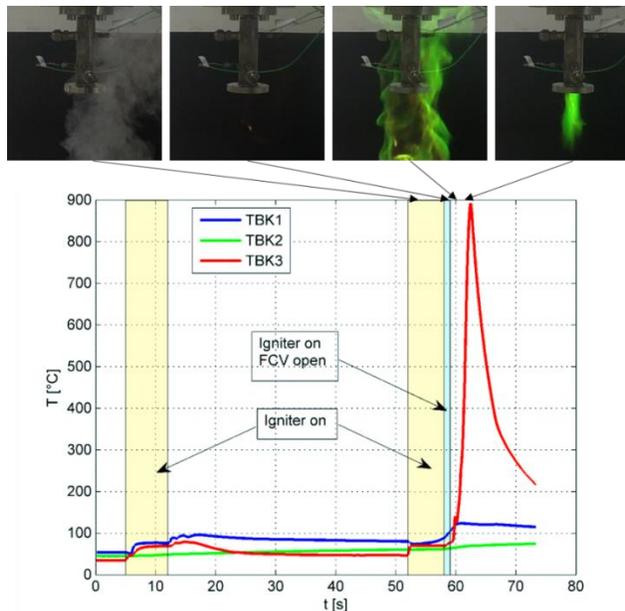

Fig. 11. Video snapshots and temperature traces from the test Porous-B 085. Propellant: LMP-103S

The tests with the setup Porous-B showed that thermal ignition of ADN-based propellants is possible. Further tests will be necessary to determine if the setup is suitable to obtain sustained combustion.

5. Conclusions

ADN-based monopropellants are attractive replacements for hydrazine in propulsion applications. In the EU Horizon2020 project RHEFORM new technologies are developed in order to improve liquid ADN-based propulsion systems. The present work is in particular focused on the innovative ignition methods developed in the framework of the project. Both catalytic and thermal igniters have been considered. The catalysts manufactured have two kinds of catalyst supports, granulated and monolithic. Different granulated support materials have been tested, including materials which were not available commercially and were synthetized in the project (silicon-doped alumina and two types of hexaaluminates). The support materials were characterized through XRD and nitrogen sorptiometry. The impregnation with different active phase was successfully conducted. The monolithic supports were 3D printed with an innovative process called Lithography-based Ceramic Manufacturing (LCM). Four different ceramics were successfully printed with this method: cordierite, aluminum oxide, magnesium oxide and silicon nitride. Three different designs were implemented: straight channel, cellular structure and polyhedral structure. The monolithic supports required a washcoat layer to increase their specific surface area. Methods to apply the layer on the monoliths were developed in the project. Finally, the monoliths were impregnated with different active phases.

Tests on the thermal ignition of ADN-based propellants were conducted with a torch igniter. Initially a cylindrical combustion chamber without flame (reaction) holding devices was tested. No ignition with both baseline propellants (LMP-103S and FLP-106) was obtained. Based on the reference setup, modifications were made. This included porous materials to facilitate the vaporization of the propellant and to anchor the decomposition reaction. With one of these setups it was possible to achieve ignition of the propellant. It remains to be tested if sustained combustion can be achieved with the same configuration.

References

[1] A. S. Gohardani, J. Stanojev, A. Demairé, K. Anflo, M. Persson, N. Wingborg and C. Nilsson, "Green space propulsion: Opportunities and prospects," *Progress in Aerospace Sciences,* vol. 71, pp. 128-149, 2014.

[2] K. Anflo and B. Crowe, "In-Space Demonstration of an ADN-based Propulsion System," in *47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, San Diego, California, AIAA 2011-5832, 2011.

[3] M. Negri, "Replacement of Hydrazine: Overview and First Results of the H2020 Project Rheform," in *6th European Conference for Aeronautics and Space Sciences (EUCASS)*, Krakow, PL, 2015.

[4] W. Zhang, *Experimental and Computational Analysis of Random Cylinder Packings,* Baton Rouge, LA: Doctoral Dissertation, Louisiana State University and Agricultural & Mechanical College, 2006.

[5] M. Schwentenwein and J. Homa, "Additive manufacturing of dense alumina ceramics," *International Journal of Applied Ceramic Technology,* vol. 12, no. 1, pp. 1-7, 2015.

[6] A. D. Lantada, A. de Blas Romero, M. Schwentenwein, C. Jellinek and J. Homa, "Lithography-based ceramic manufacture (LCM) of auxetic structures: present capabilities and challenges," *Smart Materials and Structures,* vol. 25, no. 5, 2016.

[7] T. W. Price and D. D. Evans, "The Status of Monopropellant Hydrazine Technology," Jet Propulsion Laboratory, Pasadena, California, USA, Technical Report TR-32-1227, 1968.

[8] R. E. Albers, "Characterization of the performance of an industrial monolith reactor by accurate mapping of temperature differences," *Catalysis Today,* vol. 105, no. 3-4, pp. 391-395, 2005.

[9] W. Zhang, *Experimental and Computational Analysis of Random Cylinder Packings,* Baton Rouge, LA, 2006.