THERMAL IGNITION OF ADN-BASED PROPELLANTS

M. Negri, M. Wilhelm, C. Hendrich

michele.negri@dlr.de

DLR – German Aerospace Center

Institute of Space Propulsion

Lampoldshausen, D-74239 Hardthausen, Germany

ABSTRACT

Thermal igniters are attractive for ADN thrusters as they allow a more prompt ignition and may be better suited for larger engines (100-500 N) compared to the currently used preheated catalysts. The results of an experimental campaign conducted on the ignition of two ADN-based monopropellants (LMP-103S and FLP-106) with a torch igniter are presented. Several combustion chamber configurations have been tested to facilitate the ignition. Through the use of porous inlays in the chamber, ignition of both propellants was achieved. It was not possible to achieve sustained combustion.

KEYWORDS:

Green propulsion, orbital propulsion, thermal ignition, ADN, monopropellant

1 INTRODUCTION

Hydrazine and its derivatives have been the standard propellants for spacecraft propulsion system since the 1960s, but they are highly toxic and carcinogenic. New regulations may lead to restriction of their use in the mid-term. Ammonium dinitramide (ADN, NH_4^+ $N(NO_2)_2^-$) based monopropellants are extremely promising as hydrazine replacement. They have a lower overall life cycle cost due to simplified handling, higher specific impulse and higher density compared to hydrazine [1].

Currently ADN-based thrusters are ignited with a pre-heated catalyst. The 1 N thruster from ECAPS features a 10 W heater. The pre-heating time is 30 minutes. In the case of the PRISMA thruster the maximum load during preheating was 9.25W and 8.3W during firing [2] Cold start is not possible: the decomposition starts only if the catalyst has reached its operational temperature of 350 °C. This is a limitation of ADN thrusters compared to hydrazine ones: the catalysts currently used for hydrazine (S405 or similar) are cold start capable, even if preheating is often used to increase the lifetime of the catalyst. Cold start capability could be important if the thruster has to be used in emergency situation, where there is no time to pre-heat it. A reduction in preheat power would also be a benefit for small satellites, where the available power is limited [2].

The preheating power for larger hydrazine thrusters remains limited to some tenths of Watts. For example, the preheating power for the Aerojet 440 N thruster is 13.1 W [3]. On the other hand the preheating power requirements for ADN catalysts increase strongly for larger thruster. This is due to the fact that most of the power is used to evaporate the propellant and the propellant mass flow rate increase nearly linearly with the thrust.

Due to these limitations, the possibility to develop a cold start capable igniter for ADN propellants is currently studied in the EU Horizon2020 project Rheform.

1.1 The Rheform Project

Rheform is a project funded from the European‘s Union Horizon 2020 programme. The name Rheform stands 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 centers 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 small companies are involved: Lithoz and FOTEC. Finally two space companies are participating: ECAPS and ArianeGroup (AG).

Figure 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: 20 and 200 N were selected. 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 [4]. 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. At the beginning of the project, advanced ignition methods have been tested with ADN-based propellants [5]. In particular, tests were conducted at FOI with a resistive igniter and at DLR with a laser igniter. The results of the preliminary tests were not satisfactory; therefore it was decided to switch to a proven hydrogen/oxygen torch igniter.

The first tests with a torch igniter were conducted using a tubular combustion chamber and a swirl injector. In this configuration the flame generated from the igniter was quenched when the propellant was injected [6].

To facilitate the ignition porous elements were inserted in the combustion chamber. The tests with three configurations including porous elements s and with two ADN-based monopropellants (LMP-103S and FLP-106) are described in the present paper.

2 EXPERIMENTAL SETUP

2.1 Test Bench

The experimental campaign was conducted at the test bench M11.2 at Lampoldshausen, Germany. The tests described were conducted under atmospheric pressure. Two different ADN-based propellants were used: FLP-106 and LMP-103S. The propellant was stored in two 1-liter stainless steel tanks and pressurized with nitrogen. The mass flow rate of propellant was estimated by running the same sequence with water and collecting and weighting the amount of water from the chamber and finally correcting for the different density of the propellants (FLP-106: 1360 Kg/m3, LMP-103S: 1250 Kg/m3). A turbine was installed in the feeding line, but the mass flow rates during the tests were below the measuring range.

2.2 Torch Igniter

The type of torch igniter is the same used in several test benches at DLR. In the typical setting it gives a thermal output of 12 kW with a firing time of 1 s. During the first tests it was found that when the igniter was used in this setting the temperature of the gasses generated was too high and would lead to a melting of the porous material. On the other hand if the operating time was reduced the copper inlay did not heat sufficiently. Therefore, it was necessary to test other operating setting to reduce the thermal output and increase the firing time. Finally a good solution was found operating the igniter with two firing separated by a 40 s pause. The thermal power was ranged between 2.5 and 3 kW, allowing two firings up to 9 s.

2.3 Configuration tested

The preliminary tests conducted with the torch igniter showed that with a basic tubular chamber no ignition of the propellant could be achieved [6]. It was assumed that some kind of devices are required in the combustion chamber to facilitate the heat transfer between the hot gasses generated by the torch igniter and the propellant and to increase the propellant residence time in the chamber. To try and achieve thermal ignition an improvement of the demonstrator design based on the tests conducted was conducted. Three different designs were so built and tested, called respectively Porous-A, Porous-B, and Porous-C.

2.3.1 Configuration Porous-A

The test configuration Porous-A was used for the test from number 001 to number 033. A drawing of the configuration Porous-A is shown in Figure 30. The configuration used a copper inlay and two discs of porous materials. The 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 flow through the material. The second porous material (Sika-B 150 bronze) was designed to be preheated by the torch, mainly through heat conduction from the copper inlay, which was directly heated by the torch. The heated porous material was designed to vaporize the propellant and act as reaction holding device. The good thermal conductivity of the bronze porous material in combination with the copper inlay facilitated the heat feedback from the reaction zone back in the propellant.

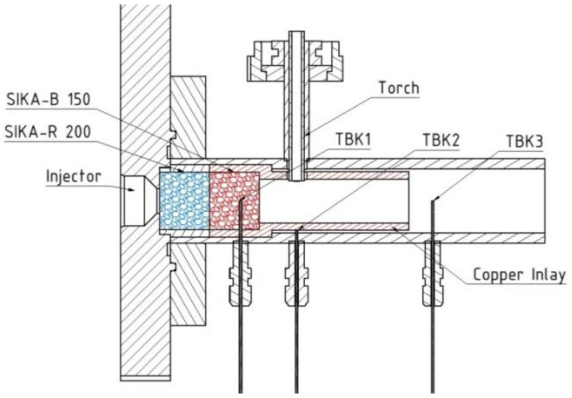


Figure 2. Setup Porous-A. TBK1, 2, 3 are thermocouples.

The torch igniter was placed radially w.r.t. the chamber to heat the copper inlay and the SIKA-B 150 porous material. A microshowerhead injector 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.

2.3.2 Configuration Porous-B

The test configuration Porous-B was used in the test from number 034 to 151. The setup Porous-B was a modification to the setup Porous-A. A schematic draft of the setup is given in Figure 3. 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, allowing a more uniform temperature distribution compared to less conductive materials. The position of the torch igniter was changed with respect to setup A: in this setup the torch was mounted on the face plate, so that the combustion products of the torch went through both porous inlays. The advantage of this setup was a better heat exchange between the hot gasses from the torch and the porous disc. This allowed to obtain higher temperatures of the porous material compared to setup A. The power of the torch had to be reduced to avoid melting the porous inlay.

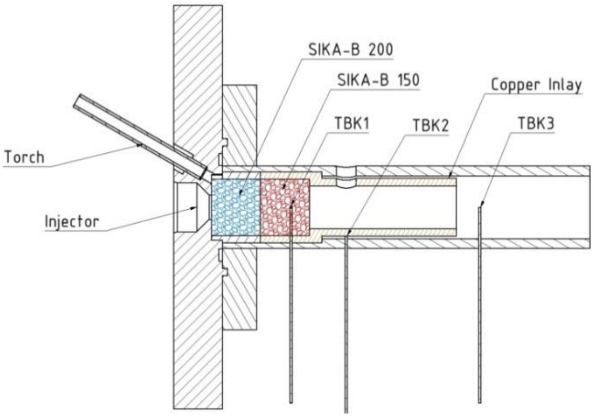


Figure 3. Setup Porous-B.

The diagnostic of the setup B was improved after the first series of tests: in the tests from 079 to 151 an additional thermocouple (T porous) was added, which measures the temperature in the centre of the SIKA-B 200 porous disc. The position of this thermocouple is shown in Figure 4.

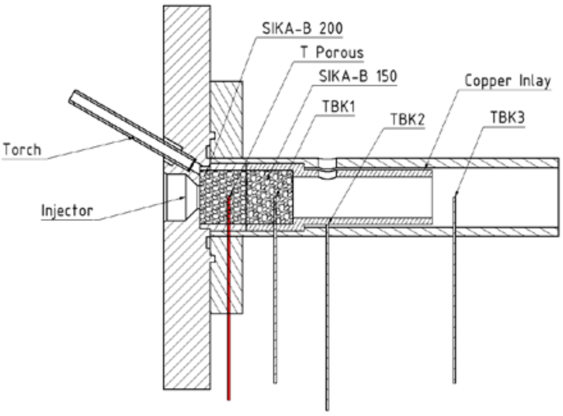


Figure 4. Setup Porous-B with the additional thermocouple T Porous.

2.3.3 Configuration Porous-C

The test configuration Porous-C was used in the test from number 208 to 215. The setup Porous-C was similar to Porous-A, but it was modified to improve the heat feedback from the flame in the porous material. A drawing of the setup C is shown in Figure 33. In the setup A a stainless steel ring and steel porous material were used. In the setup C they were removed and instead the copper inlay was longer, so that both the porous discs were located in the inlay. This allowed a more homogenous heating of the porous material. Both discs were made of bronze in order to have a good conductivity. In the setup B the torch was placed on the faceplate, and therefore the temperature of the porous material was higher and closer to the faceplate itself and decreased towards the end of the porous material. In the setup C the torch igniter was placed after the porous material. Goal was to have the highest temperatures at the end of the porous material to facilitate the ignition of the vaporized propellant.

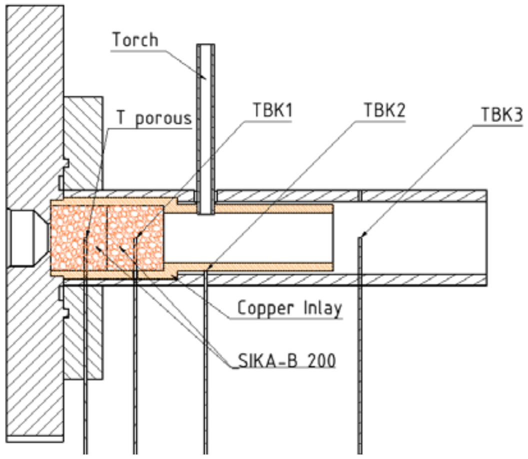


Figure 5: Setup Porous-C

Table 1: Overview of the operating setting for selected tests.

	Prop.	Setup	Torch Power	Tank Pressure	Propellant Mass flow rate	Test –Sequence [ms]				
			[kW]	[bar]	[g/s]	Torch 1st firing	Pause	Torch 2nd firing	Torch FCV open	Only FCV open
028	LMP-103S	A	6.37	7.0	16.1	3000	40000	3000	500	-
081	LMP-103S	B	2.49	2.2	3.7	6000	40000	5000	1000	-
145	FLP-106	B	2.82	3.3	4.4	7000	40000	6000	3000	-
210	FLP-106	C	2.87	3.2	4.3	9000	40000	6000	3000	-
212	FLP-106	C	2.86	3.4	4.4	9000	40000	6000	3000	2000
214	FLP-106	C	2.86	5.1	5.3	9000	40000	5000	5000	-

3 RESULTS

More than 200 hot firing tests were conducted. In the present work only the results of some of the most representative tests are presented. A table with an overview of the settings for the selected tests is given in Table 1. The pressure traces of these tests are shown in Table 2.

3.1.1 Test 028

Frame shots from the test 028 are shown in Figure 6. The propellant feeding pressure was 7 bar, which was the highest feeding pressure in this campaign. The amount of propellant injected was correspondingly quite large. The amount of condensed propellant coming out of the chamber was quite limited, but complete vaporization of the propellant was not achieved. After closure of the FCV, the propellant left in the chamber burned with a green flame. A corresponding increase in temperature of the chamber (TBK3) was recorded. After the green flame formation of brown smoke was observed.

3.1.2 Test 081

The mass flow rate of propellant was lower compared to test 028. No condensed propellant coming out of the chamber was observed, as can been seen in the frameshots in Figure 7. Initially the propellant vaporized forming brown vapours. Then the vapours ignited with a bright green flame. Probably the ignition was caused from the vaporized propellant coming in contact with the hot flame tube of the torch igniter outside the thruster. The combustion extended then rapidly to the remaining vaporized propellants and then the combustion was anchored in the chamber. The initial flame looked like a diffusion flame, probably due to the combustion of the volatile components of LMP-103S (methanol and possibly ammonia) with atmospheric oxygen. It was assumed that the more bright yellowish flame from the combustion chamber is due to the decomposition and combustion of ADN. Towards the end of the test the diffusion flame was observed again.

The temperature of the porous material measured from the thermocouple TBK1 is relatively low, and remained lower that 120°C also during the combustion of the propellant.

3.1.3 Test 145

Frame shots from the test 145 are shown in Figure 8. In this test complete vaporization of the propellant was achieved and the exhausts were almost colourless. A single puff of brown smoke was produced toward the end of the test. No flame was observed. The temperature in the second porous material (TBK1) reached 500 °C after the injection of propellant.

3.1.4 Test 210

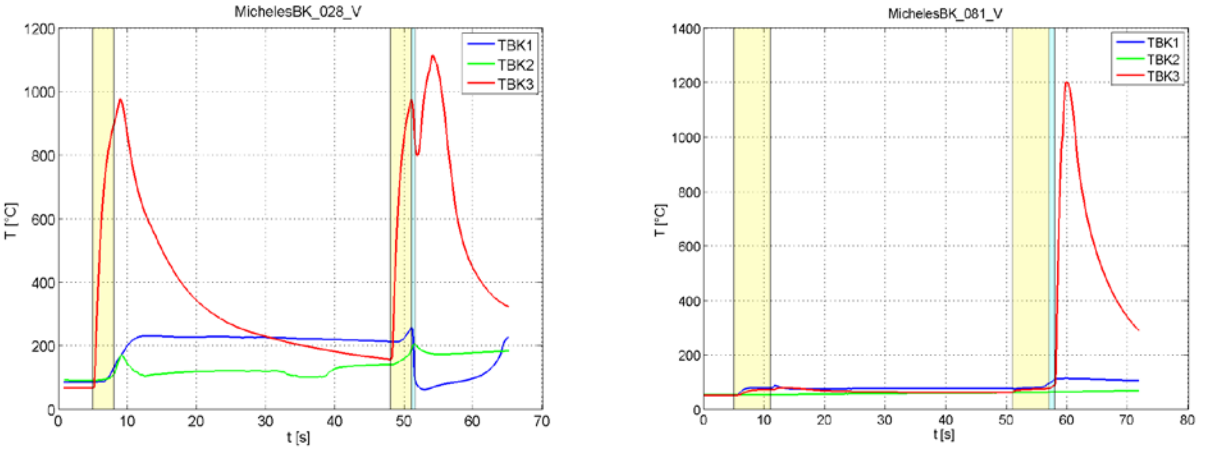
In this test ignition of the propellant FLP-106 was achieved. The propellant burned with a green flame as long as the torch is on, as shown in Figure 9. The temperature in the combustion chamber remained around 500°C, which probably indicates that the combustion takes place mostly outside the chamber. The combustion stopped short after the torch was turned off. Then some propellant leaved the chamber in condensed form. A spontaneous re-ignition of propellant rest was observed. Test 212

The propellant burned with a green flame as long as the torch is on, as shown in Figure 10. The temperature in the combustion chamber increased with the injection of propellant as long as the torch was on, reaching almost 700°C. No sustained combustion is achieved: the flame is quenched 0.4 after the shutdown of the torch. Then some propellant leaved the combustion chamber in condensed state.

3.1.5 Test 214

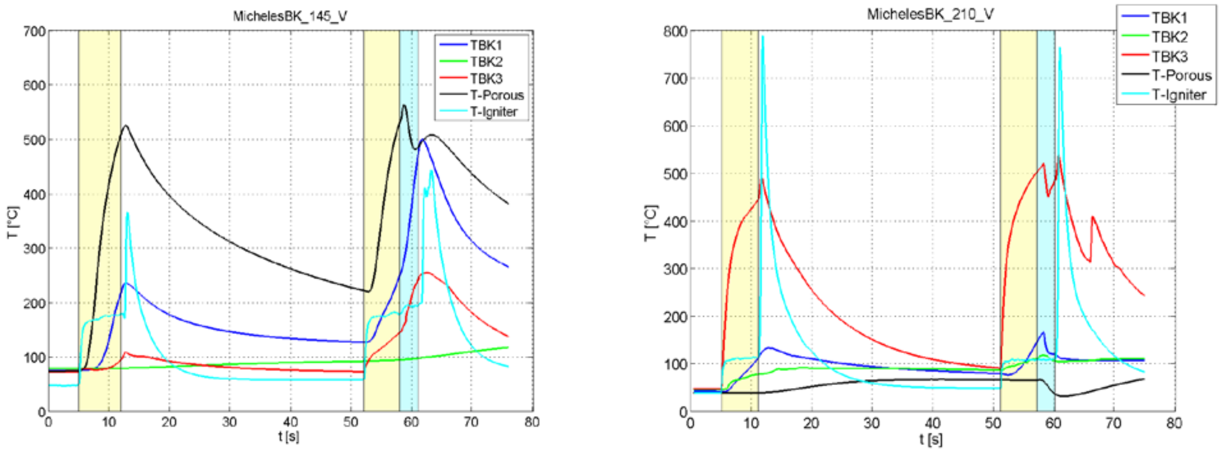
The test was conducted with a 8 mm nozzle. The feeding pressure was higher than in the previous tests. The injection of the propellant leaded a drop in temperature both in the porous material (T porous and TBK1) as well as in the combustion chamber (TBK3). The torch was active all the time during propellant injection. After an initially green flame the exhaust of the thruster were almost colourless. After the shutdown a white smoke was produced.

Table 2: Temperature traces measured during selected tests



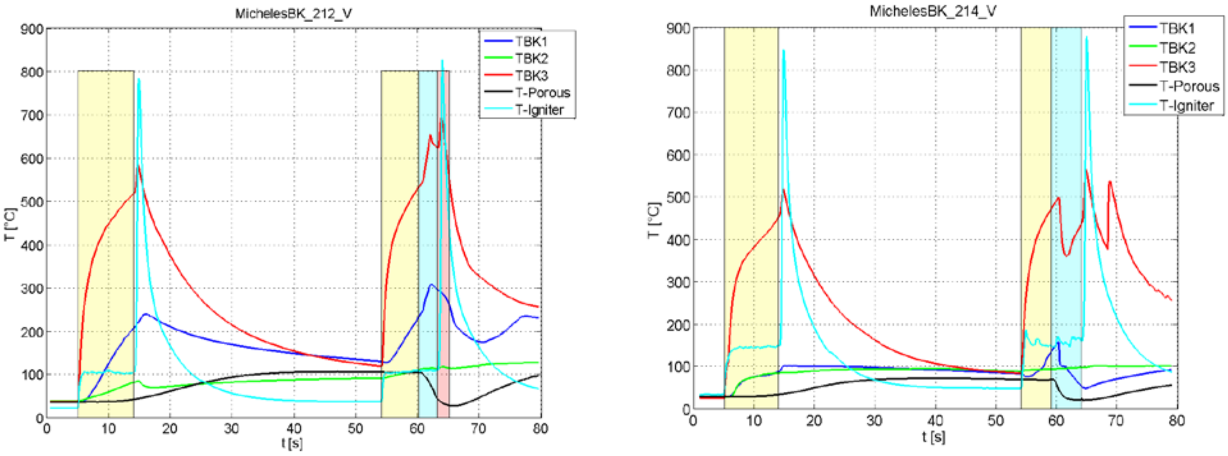
Test 028

Test 081



Test 145

Test 210



Test 212

Test 214

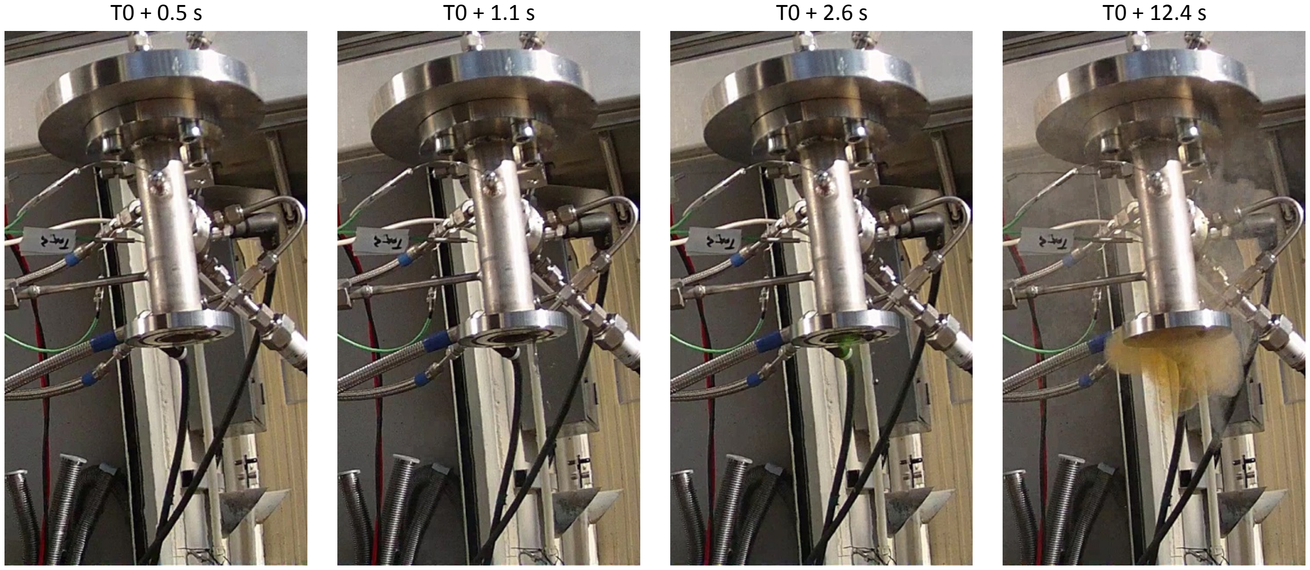

T0 + 0.5 s T0 + 1.1 s T0 + 2.6 s T0 + 12.4 s

Figure 6: Frame shots of the test 028

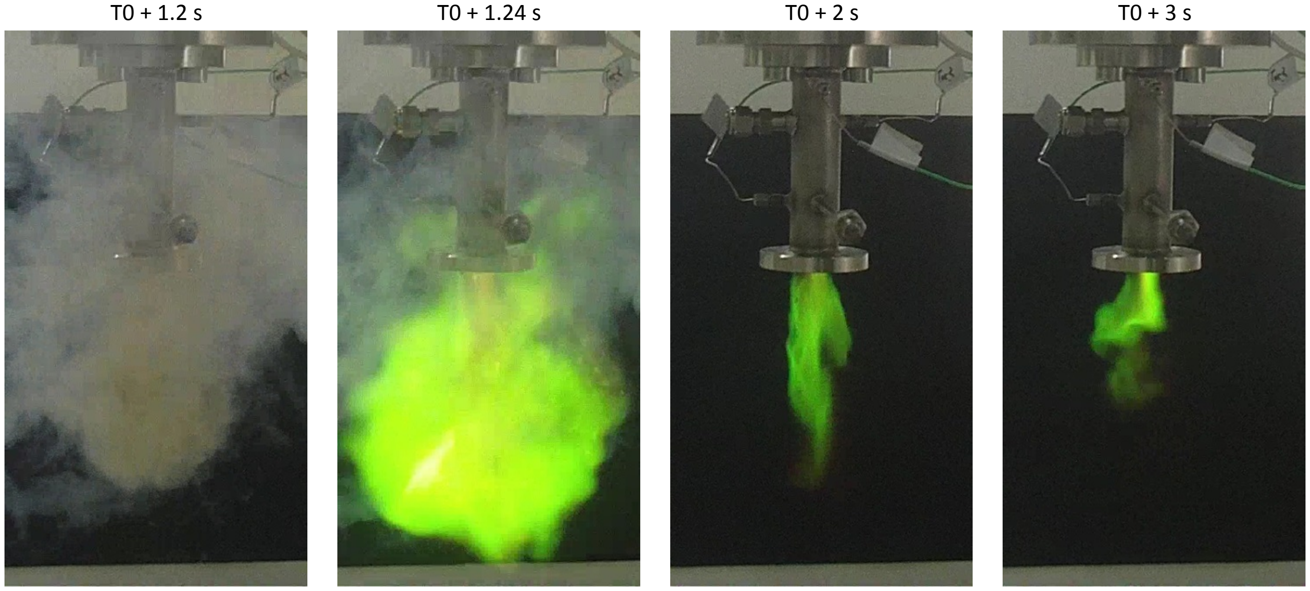

T0 + 1.2 s T0 + 1.24 s T0 + 2 s T0 + 3 s

Figure 7: Frame shots of the test 081


T0 + 1s T0 + 2s T0 + 2.8 s

Figure 8: Frame shots of the test 145


T0-0.04 s
T0+1s
T0+2s
T0+5s
T0+9s
T0+10s

Figure 9: Frame shots of the test 210. The green LED is off when the FCV is open (2nd and 3rd frame shots).

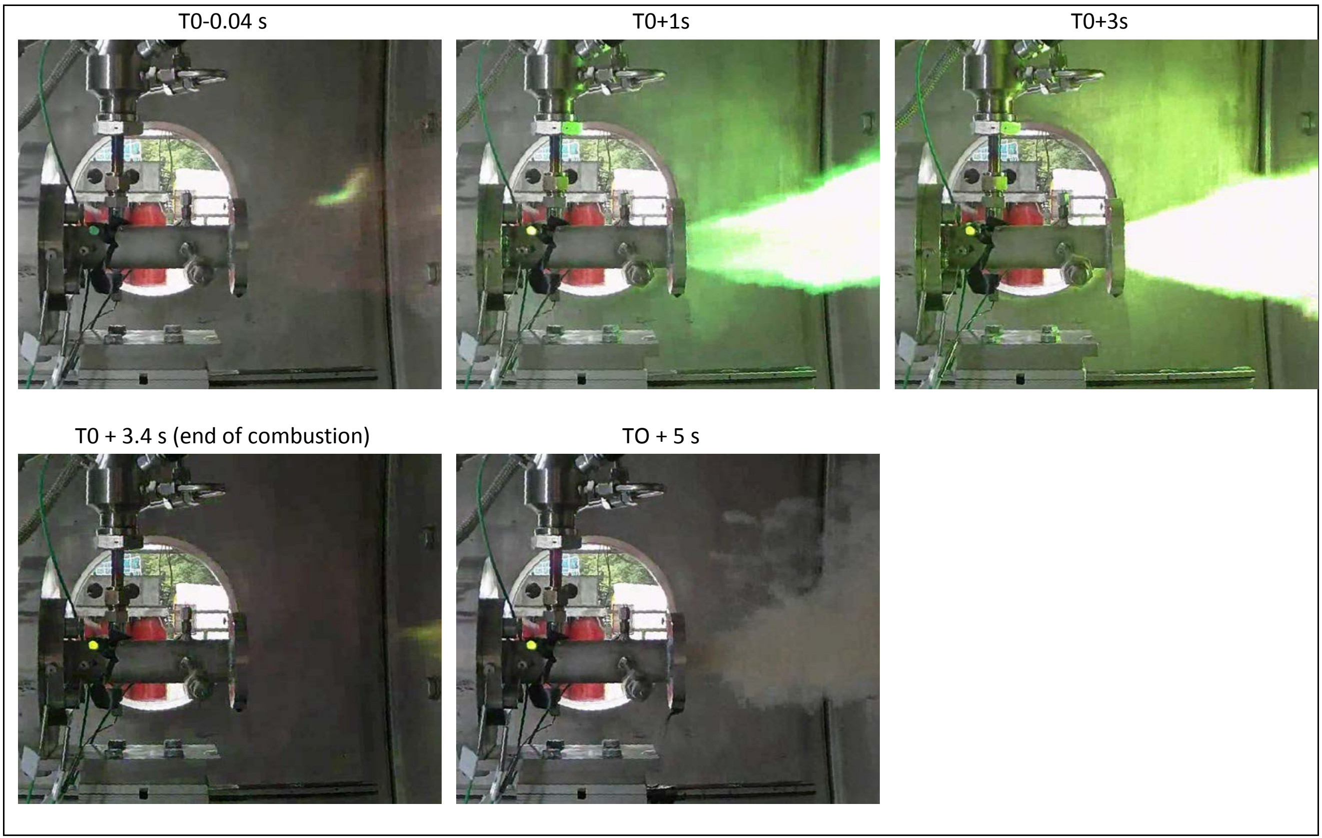
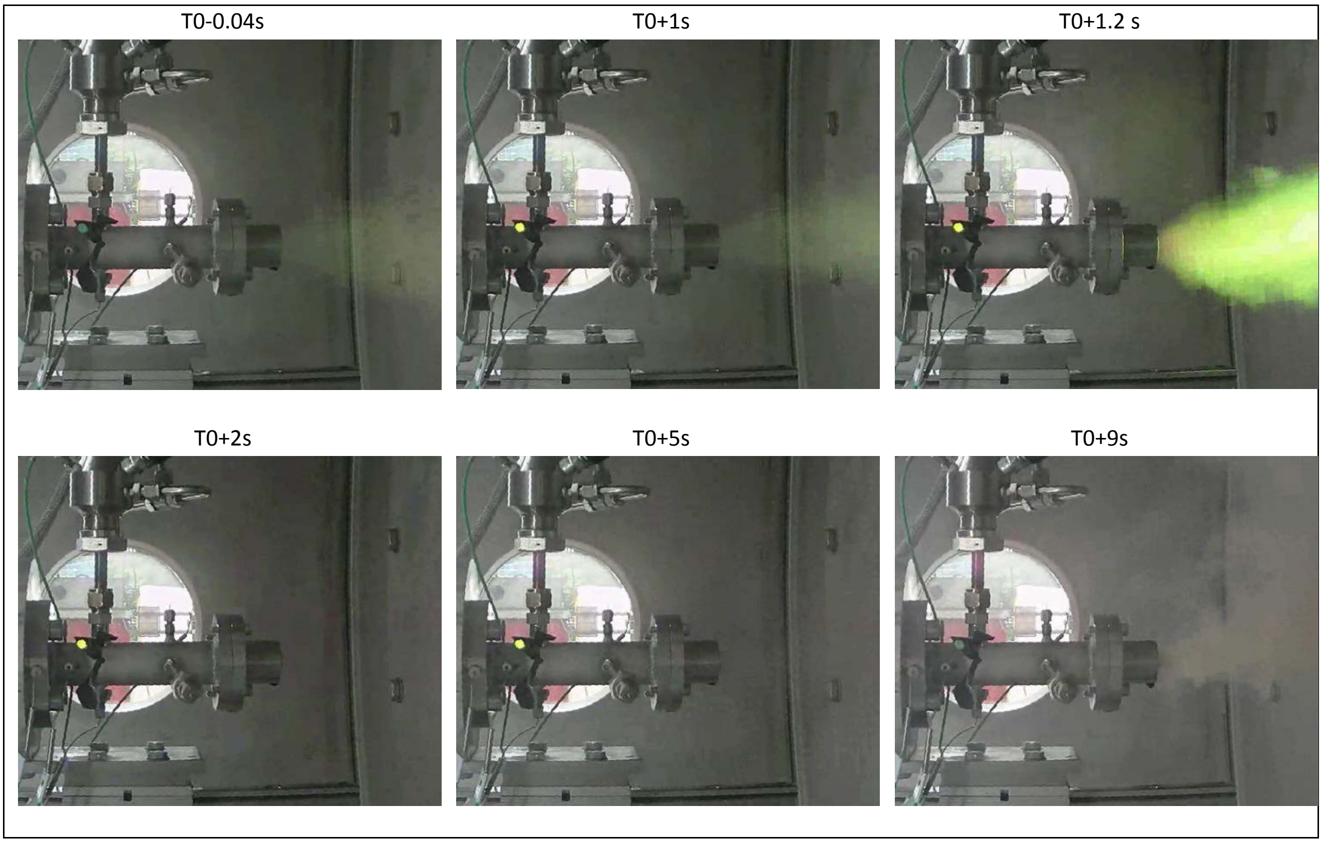

T0-0.04 s
T0+1s
T0+3s
T0 + 3.4 s (end of combustion)
TO + 5 s

Figure 10: Frame shots of the test 212. . The green LED is off when the FCV is open (2nd to 5th frame shots).



T0-0.04s
T0+1s
T0+1.2 s
T0+2s
T0+5s
T0+9s

Figure 11: Frame shots of the test 214

4 DISCUSSION

Thermal ignition of both LMP-103S and FLP-106 was achieved in an open combustion chamber (without nozzle). The propellants burned with a green flame. The colour of the flame came probably from the copper inlay and the bronze porous material.

No clear combustion was observed testing the configuration Porous A.

Combustion was observed with configuration Porous-B in the tests 081, 085 and 088. The combustion happened in three phases as shown in Figure 12. In the first phase a diffusion flame was observed. Probably this flame was generated by the combustion of the volatile components of LMP-103S (methanol and possibly ammonia) with atmospheric oxygen. In the second phase the flame was anchored in the chamber and produced a loud hissing sound. It is assumed that in this phase ADN decomposes and combusts. This hypothesis is supported by the high temperatures recorded in the combustion chamber (TBK3). In the test 088 this phase was not observed. Instead the flame remains a diffusion flame. The temperature in the combustion chamber remained in case low (below 100 °C). Finally in the third phase, which takes place several second after the closure of the FCV, a diffusion flame was observed. This was generated by the combustion of the combustion of the volatile components of leftover propellant with atmospheric oxygen. These tests were conducted with the thruster in vertical position. Interestingly no flame was observed when the tests were repeated with the thruster in horizontal position (test 106, 109, 110).

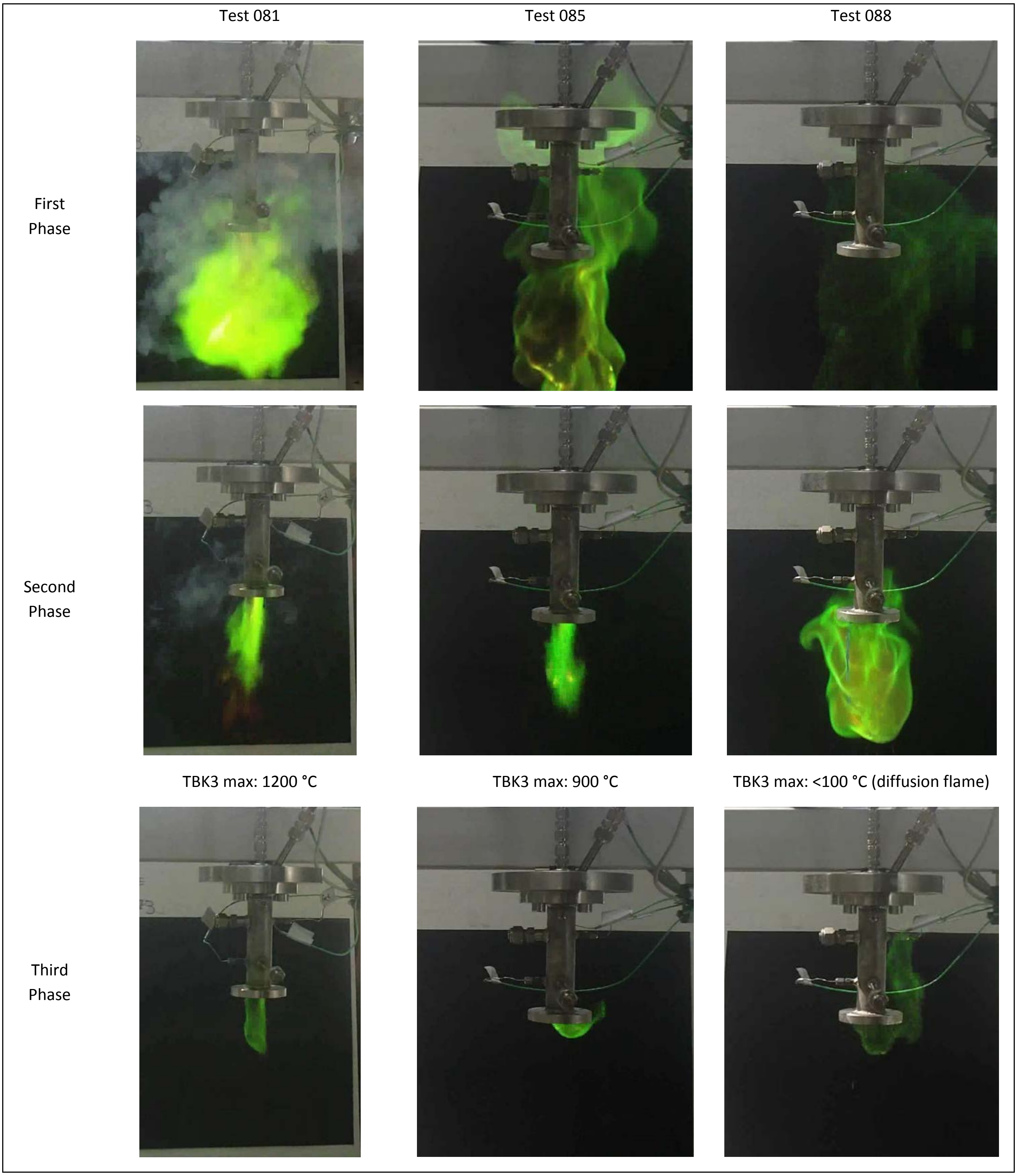


Figure 12: Three-phase combustion observed with configuration B.

An explanation for the different behaviour is that a more uniform radial distribution of the propellant is obtained with the thruster in vertical position. On the other hand, when the thruster is horizontal, the gravity influences the radial distribution of the propellant, leading to having more propellant in the lower part of the porous material. Such non uniform distribution did not allow reaching the conditions necessary for ignitions, i.e. the propellant was not heated enough. Combustion of FLP-106 was observed with configuration Porous-C in test 210 and 212. These tests were conducted without nozzle. A very bright green flame was generated as soon as the propellant was injected. The test 212 showed that sustained combustion was not achieved: the green flame disappeared shortly after the shutdown of the torch, even if the FCV was still open. No flame was observed in the tests conducted with configuration Porous-C and a nozzle.

5 CONCLUSIONS

The tests conducted clearly showed that a flame holding device facilitates the ignition of the propellants. The effects of the porous material are:

- store thermal energy to vaporize the propellant
- increase the residence time of the propellant in the combustion chamber, so increasing the chances of achieving complete vaporization and ignition.
- facilitate the ignition.

The tests with the configuration Porous-C clearly indicated that a combustion of the propellant can be achieved when the vaporized propellant wasexposed to an ignition source, in this case the hot gasses generated from the torch igniter. A similar situation took place in the tests 081 and 085 (configuration: Porous B) were the diffusion flame generated by the combustion of methanol in air facilitated the ignition of ADN.

None of the configuration tested enabled a sustained combustion. An optimization of design of the chamber to increase the heat feedback from the flame to the vaporization area may help to achieve this goal.

6 ACKNOWLEDGMENTS

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 640376.

The authors would like to thank the M11 team for the help during test conduction.

7 REFERENCES

[1] A. S. Gohardani *et al.*, “Green space propulsion: Opportunities and prospects,” *Prog. Aerosp. Sci.*, vol. 71, pp. 128–149, 2014.

[2] S. A. Whitmore, D. P. Merkley, S. D. Eilers, and T. L. Taylor, “Hydrocarbon-Seeded Ignition System for Small Spacecraft Thrusters Using Ionic Liquid Propellants,” *27th Annu. AIAA/USU Conf. Small Satell.*, 2013.

[3] Aerojet, “Monopropellant Thrusters Data Sheet,” 2006. [Online]. Available: https://www.rocket.com/files/aerojet/documents/Capabilities/PDFs/Monopropellant Data Sheets.pdf.

[4] M. Negri, “Replacement of Hydrazine : Overview and First Results of the H2020 Project Rheform,” in *6Th European Conference for Aeronautics and Space Sciences (Eucass)*, 2015, pp. 1–12.

[5] M. Negri, C. Hendrich, M. Wilhelm, D. Freudenmann, and H. K. Ciezki, “Thermal ignition of ADN-based propellants,” in *Space Propulsion Conference*, 2016, no. 2, pp. 1–12.

[6] M. Negri, “Technology development for ADN-based green monopropellant thrusters – an overview of the Rheform project,” in *7th European Conference for Aeronautics and Space Sciences (EUCASS)*, 2017, pp. 1–13.