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Thermal Ignition of ADN-Based Propellants

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Abstract: Ammonium dinitramide (ADN, NH_4^+ $N(NO_2)_2^-$) based monopropellants are extremely promising as hydrazine replacement. 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, however, to achieve sustained combustion under the chosen test conditions.

Keywords: Green propulsion · orbital propulsion · thermal ignition · ADN · monopropellant

1 Introduction

Hydrazine has been the standard monopropellant for spacecraft propulsion system since the 1960s, but it poses serious health risks, being highly toxic and carcinogenic. All operations involving hydrazine (for example testing, shipping, fuelling) require extensive safety procedures in order to minimize the associated risks for personnel and the environment. Hydrazine requires dedicate infrastructure for storage and decontamination both at ground testing and at launch site. The additional safety equipment and procedures substantially increase the life cycle costs of hydrazine. Hydrazine reduces the flexibility of operations at launch site and increases the time required between two subsequent launches: for example the complete launch pad has to be evacuated during hydrazine fuelling. Hydrazine has been inserted in the REACH list of Substances of Very High Concern (SVHC) by the European Chemicals Agency in 2011. It may be banned in the future, and this poses a concrete risk for future missions using this propellant.

ADN-based monopropellants have been developed in order to overcome the problematic associated with hydrazine. The development of such propellants started in 1997 at the Swedish Defence Research Agency (FOI) on a contract from the Swedish Space Corporation (SSC) [1]. SSC founded in 2000 the company ECAPS (now Bradford ECAPS) in order to bring on the market green propulsion system. Through the collaboration between FOI and ECAPS the propellant LMP-103S was invented. The propulsion systems based on this propellant have currently the highest degree of maturity of any green propulsion system. Currently Bradford ECAPS is providing 19 propulsion systems for the earth observation satellites SkySat. Each propulsion system is equipped with 4×1 N thrusters. Research activities on ADN-based propulsion systems are conducted by other entities as well. The Beijing Institute of Control Engineering (BICE) has developed thrusters with 0.2 N, 1 N, 5 N, and 20 N thrust. A 1 N thruster was demonstrated in-orbit in November 2016 with a total firing time of 4250 s [2].The Lithuanian company NanoAvionics developed an ADN-based cubesat propulsion system to TRL7 with a 100 mN thruster and demonstrated it in orbit as part of the LituanicaSAT-2 mission, launched in June 2017 [3].

The advantages of ADN-based green propellants compared to hydrazine can be highlighted considering the PRISMA mission, the demonstration mission of ECAPS, where a satellite was equipped with both an hydrazine and a LMP-103S propulsion system to allow a direct comparison [4]:

- Increased performances. 8% higher specific impulse and 24% higher density, therefore smaller tank for the same mission and increased payload.
- Reduced cost. The cost for propellant, transportation and fuelling operations connected to LMP-103S were 2/3 the cost for hydrazine during the PRISMA mission.
- Faster operations at launch site. Fuelling operations for LMP-103 were performed in parallel with other launch preparation activities at the highbay, with exclusion of the tank pressurization [5].
- Increased rideshare opportunities. A secondary satellite using ADN-based monopropellant will be better ac-

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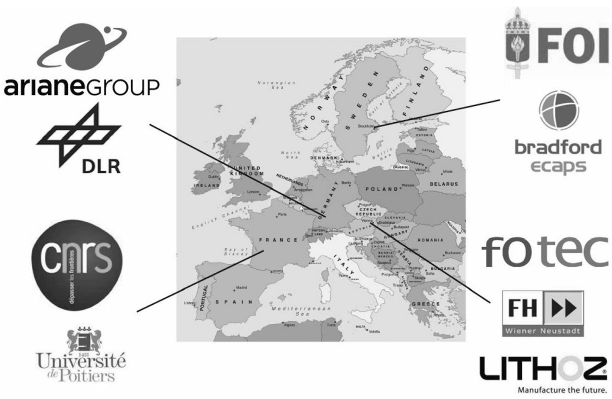

Figure 1. Rheform partners.

cepted as rideshare compared to a satellite using hydrazine, due to the safer propellant.

The present work has been conducted in the framework of the Rheform project [6], [7]. Rheform was 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 ran from January 2015 to the end of 2017. The Rheform consortium comprised 9 entities from 4 European countries: Austria, France, Germany and Sweden, as shown in Figure 1. The present work is focused on one of the research fields covered by Rheform, namely the development of thermal ignition systems for ADN-based monopropellants.

Currently ADN-based thrusters are ignited with a preheated 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 9.25 W and 8.3 W during firing [8]. 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 [8]. The preheating power for larger hydrazine thrusters remains limited to some tens of Watts. For example, the preheating power for the Aerojet 440N thruster is 13.1 W [9]. 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 liquid components of the propellant and therefore the propellant mass flow rate increase nearly linearly with the thrust.

Due to these limitations, the possibility to develop a thermal igniter was studied in Rheform. Preliminary results of the studies on thermal ignition have been presented in ref. [10]. In the present work the results of numerous hot firing tests with different combustion chambers designed to facilitate ignition are presented.

2 Materials and Methods

2.1 Test Setup

The tests were conducted at test bench M11.2. For safety reasons the test setup was operated remotely from a separated control room. Safety was a priority, as in previous tests with ADN-based propellants several explosions did occur, due to the evaporation of water and the subsequent ignition of pure ADN exposed to high temperatures.

A schematic of the experimental setup used is shown in Figure 2. The tests described were conducted under atmospheric pressure. The propellant was stored in two 1-liter stainless steel tanks and pressurized with nitrogen. A tur-

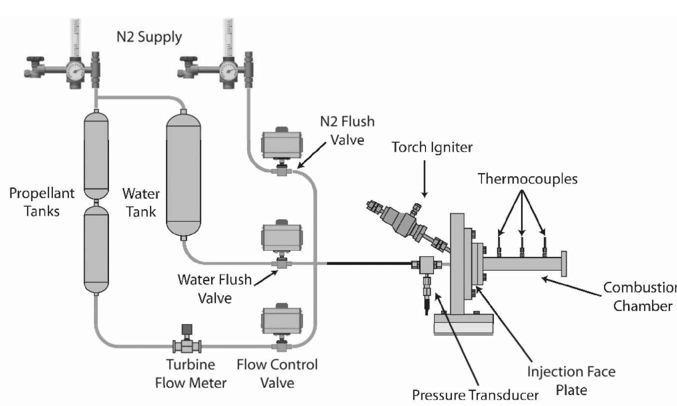

Figure 2. Schematic view of the experimental setup.

bine was installed in the feeding line, but the mass flow rates during the tests were below the measuring range. The mass flow rate of propellant was therefore estimated by running each test sequence with water, collecting and weighting it. The values obtained were corrected for the different densities of the propellants. The system allowed flushing the combustion chamber with both nitrogen and water. A torch igniter using gaseous hydrogen and oxygen was used. The feeding pressures of the two gasses were controlled by two pressure regulators. Real-time control and data acquisition was realized with an ADwin Jäger system.

2.2 Propellant Tested

Two different ADN-based propellants were used: FLP-106 and LMP-103S. The composition and density of the propellants is listed in Table 1.

LMP-103 was acquired from ECAPS. FLP-106 was prepared at DLR according to the indications from FOI.

2.3 Chamber 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 [11]. 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. Based on this idea, three different designs were built and tested, called respectively Porous-A, Porous-B, and Porous-C. The tests conducted with these 3 configurations have been numbered progressively starting at 001. All tests were conducted with a micro showerhead injector, with 45× 0.3 mm holes.

2.3.1 Configuration Porous-A

The test configuration Porous-A was used for the tests from number 001 to number 033. A drawing of the configuration Porous-A is shown in Figure 3. 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. The torch igniter was placed radially w.r.t. the chamber to heat the copper inlay and the SIKA-B 150 porous material. A micro-showerhead 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.

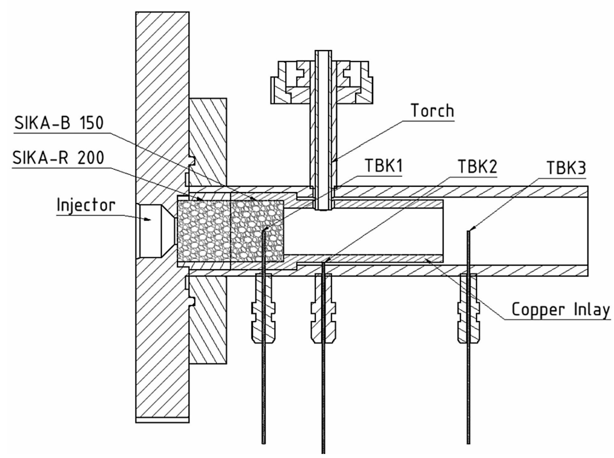

Figure 3. Setup Porous-A. TBK1, 2, 3 are the thermocouples.

Table 1. Propellants tested.

Propellant	Composition	Density
LMP-103S	63% ADN; 18.4% CH_3OH; 4.65% NH_3; 13.95 % H_2O	1250 kg/m^3
FLP-106	64.6% ADN; 23.9% H_2O, 11.5 % MMF	1360 kg/m^3

2.3.2 Configuration Porous-B

The test configuration Porous-B was used in the tests 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 4. In the setup two porous materials were used: SIKA B-200 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 stainless steel. The position of the torch igniter was changed with respect to setup A: in this setup the torch

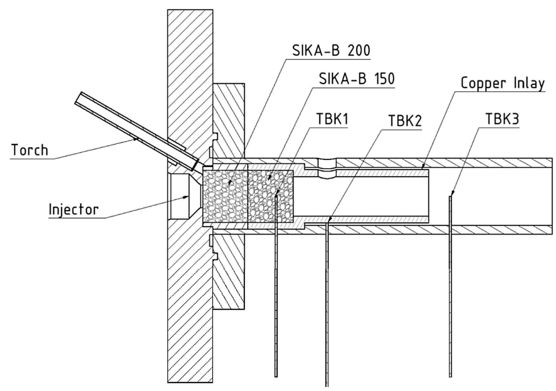

Figure 4. Setup Porous-B.

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 materials compared to setup A. The power of the torch had to be reduced to avoid melting the porous inlay.

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 center of the SIKA-B 200 porous disc. The position of this thermocouple is shown in Figure 5.

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 6. 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.

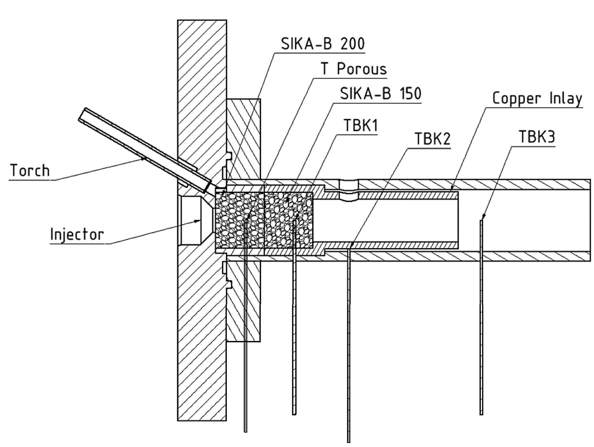

Figure 5. Setup Porous-B with the additional thermocouple T Porous.

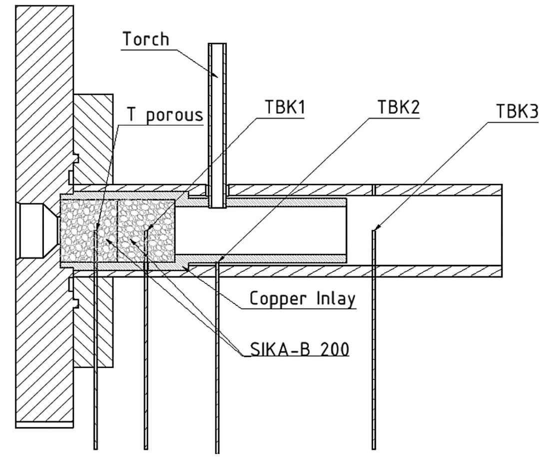

Figure 6. Setup Porous-C.

2.4 Torch Igniter

The hydrogen/oxygen torch igniter used has been developed in-house at DLR, Lampoldshausen and it is used at several test benches. 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 firings separated by a 40 s pause. The thermal power was ranged between 2.5 and 3 kW, allowing two firings up to 9 s.

Table 2. Overview of the operating setting for selected tests.

Test	Propellant	Setup	Torch power [kW]	Tank pressure [MPa]	Propellant mass flow rate [g/s]	Testsequence [ms]				
						Torch 1st firing	Pause	Torch 2nd firing	Torch FCV open	Only FCV open
028	LMP-103S	A	6.37	0.70	16.1	3000	40000	3000	500	–
081	LMP-103S	B	2.49	0.22	3.7	6000	40000	5000	1000	–
145	FLP-106	B	2.82	0.33	4.4	7000	40000	6000	3000	–
210	FLP-106	C	2.87	0.32	4.3	9000	40000	6000	3000	–
212	FLP-106	C	2.86	0.34	4.4	9000	40000	6000	3000	2000
214	FLP-106	C	2.86	0.51	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 2. The temperature traces of these tests are shown in Figure 7.

3.1 Test 028

Frame shots from the test 028 are shown in Figure 8.The propellant feeding pressure was 0.7 MPa, which was the highest feeding pressure in this campaign. The amount of propellant injected was correspondingly quite large (more than 16 g/s). A green flame was observed, but some propellant left the chamber in liquid form, even when the combustion was taking place. Corresponding to the flame an increase in temperature of the chamber (TBK3) was recorded. After the green flame stopped burning, formation of brown smoke was observed. It should be noted that the propellant need quite some time to reach the combustion chamber mouth: a delay of some 600 ms was measured in the video.

The flame observed in this test, as well as all the flames observed in the subsequent tests, had a green color caused by the combustion of copper. The metal originated from the porous materials which were made out of bronze (an alloy with 89 % copper). Copper is not compatible with both LMP-103S [12] and FLP-106S [13]. Therefore the propellants dissolved small amounts of metal when they came in contact with the porous materials. It should be noted that copper may have influenced the ignitability of the propellants acting as catalyst, similarly to what was observed in [14].

3.2 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 9. Initially the propellant gasified forming brown vapors. Then the vapors ignited with a bright green flame. The analysis of the video indicates that 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 increased during the injection of propellant, but remained relatively low (below 120 °C). This indicates that the heat feedback from the flame was larger than the heat necessary to vaporize and ignite the propellant.

3.3 Test 145

Frame shots from the test 145 are shown in Figure 10. 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. The temperature in the second porous material (TBK1) reached 500 °C after the injection of propellant. The propellant injected transferred heat from the first porous material (where T-porous is placed) to the second material (where TBK1 is placed). No ignition or flame was observed even if the propellant reached considerably high temperatures.

3.4 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 (Figure 11). 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 left over leaved the cham-

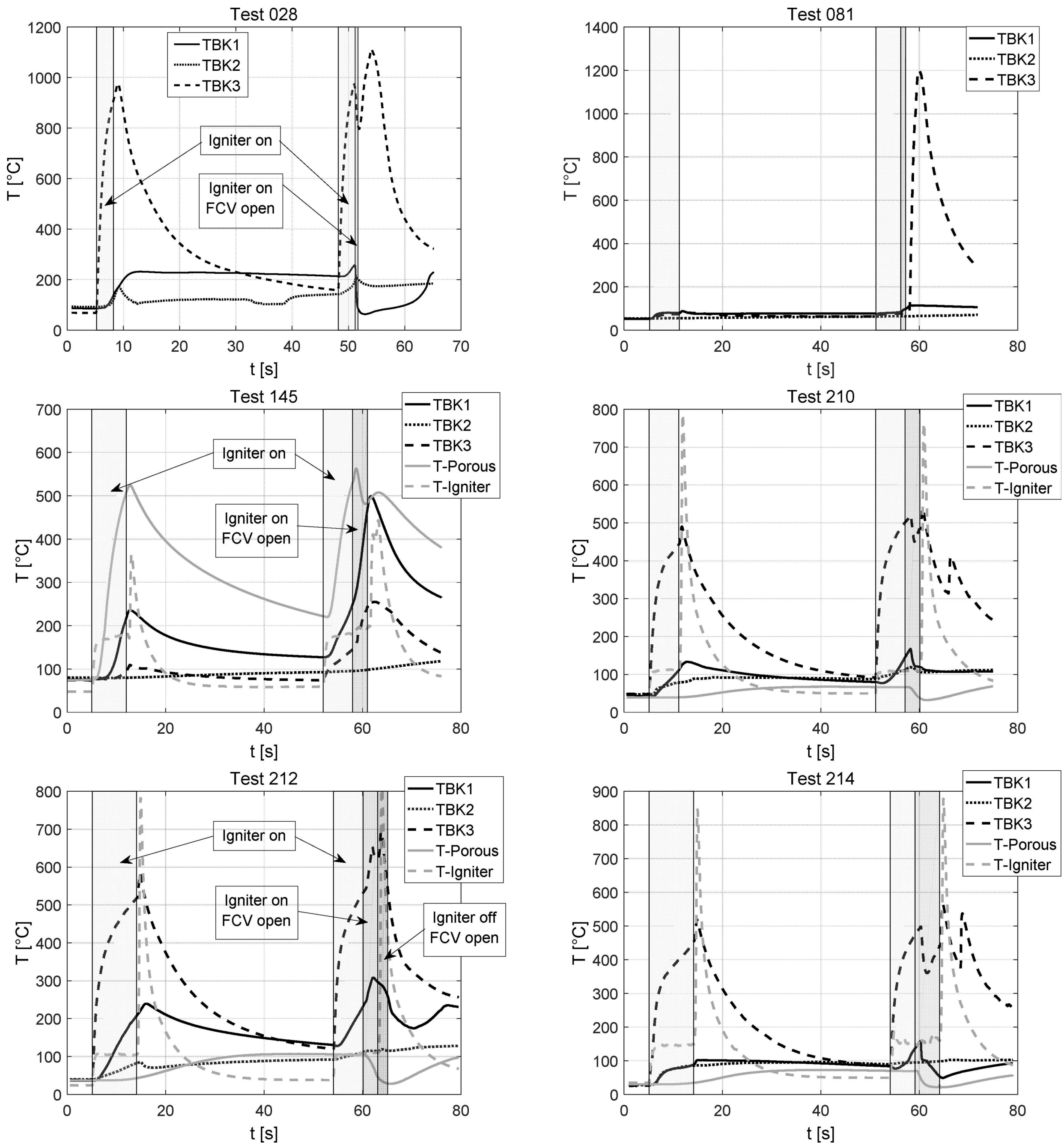

Figure 7. Temperature traces measured during selected tests.

ber in condensed form. A spontaneous re-ignition of propellant rest was observed.

3.5 Test 212

Goal of the test was to verify if sustained combustion was possible. Therefore the propellant was injected for additional 2 s after the torch was shut down. The propellant burned with a green flame as long as the torch was on (Figure 12). 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 combustion stops 0.4 after the shutdown of the torch. Then the propellant leaved the combustion chamber in liquid and vapor state.

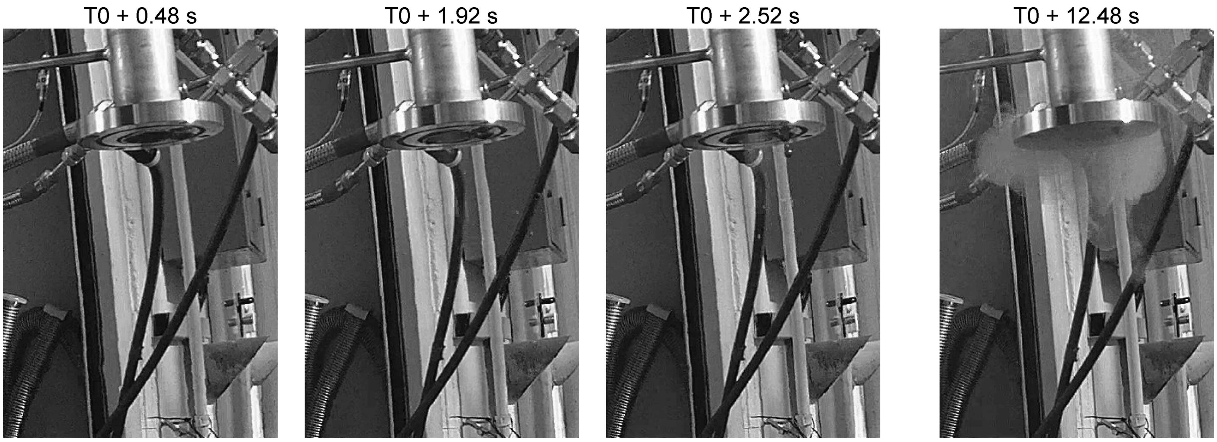

Figure 8. Frame shots of the test 028. In frame 2 and 3 a pale flame can be observed.

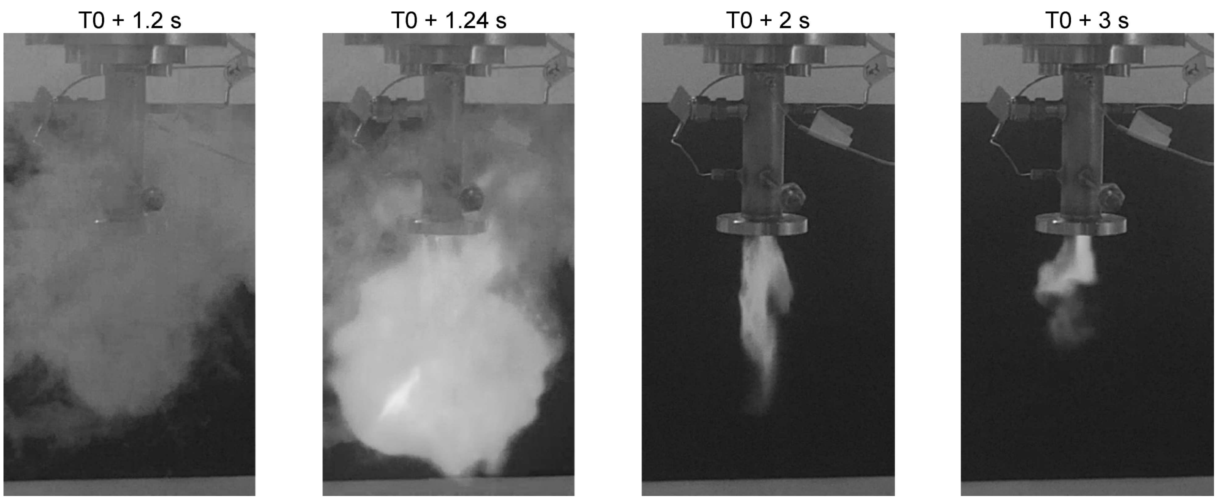

Figure 9. Frame shots of the test 081.

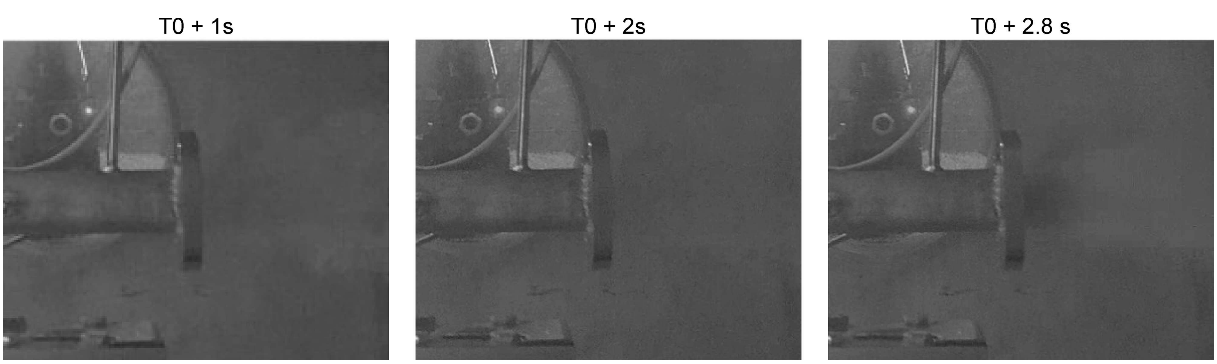

Figure 10. Frame shots of the test 145.

3.6 Test 214

The test, presented in Figure 13, was conducted with a 8 mm nozzle. The feeding pressure was higher than in the previous tests. The temperatures both in the porous material (T porous and TBK1) and in the combustion chamber (TBK3) dropped after propellant was injected. The torch was active all the time during propellant injection. After an ini-

Figure 11. Frame shots of the test 210. The LED is on when the FCV is open (2nd and 3rd frame shots).

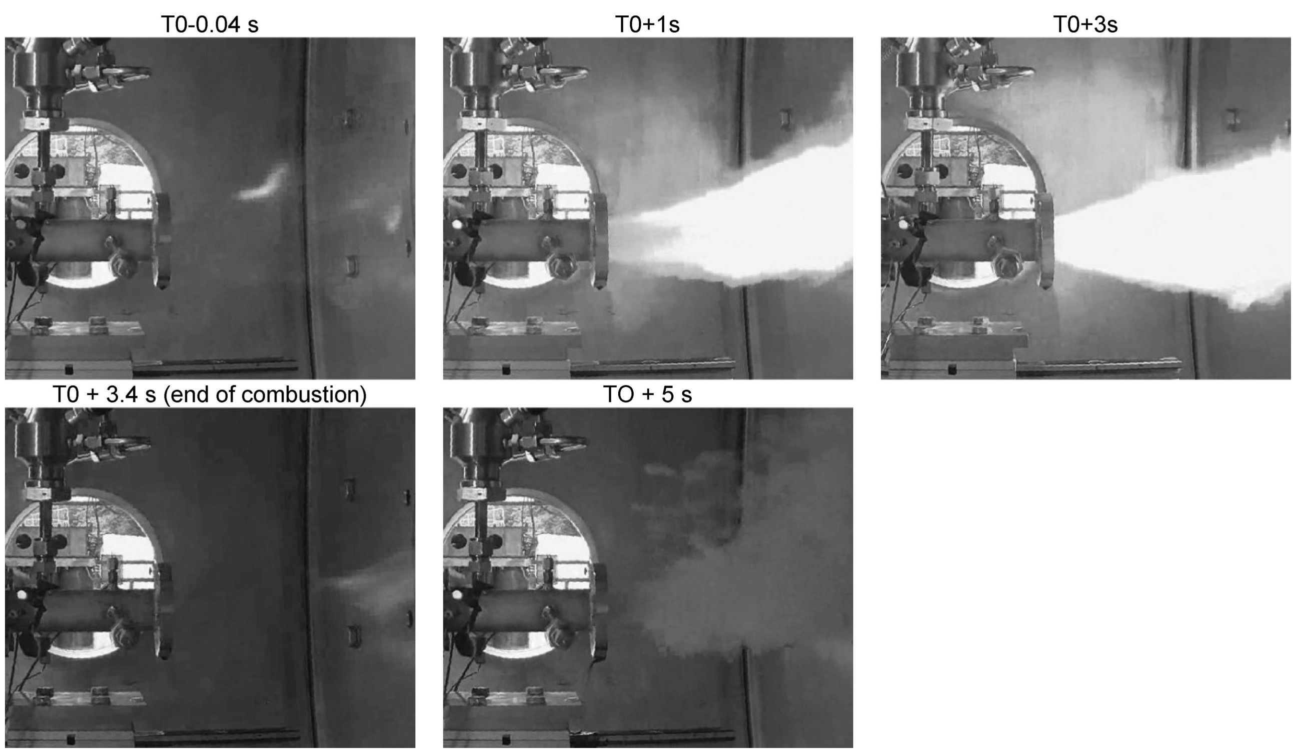

Figure 12. Frame shots of the test 212. The LED is on when the FCV is open (2nd to 5th frame shots).

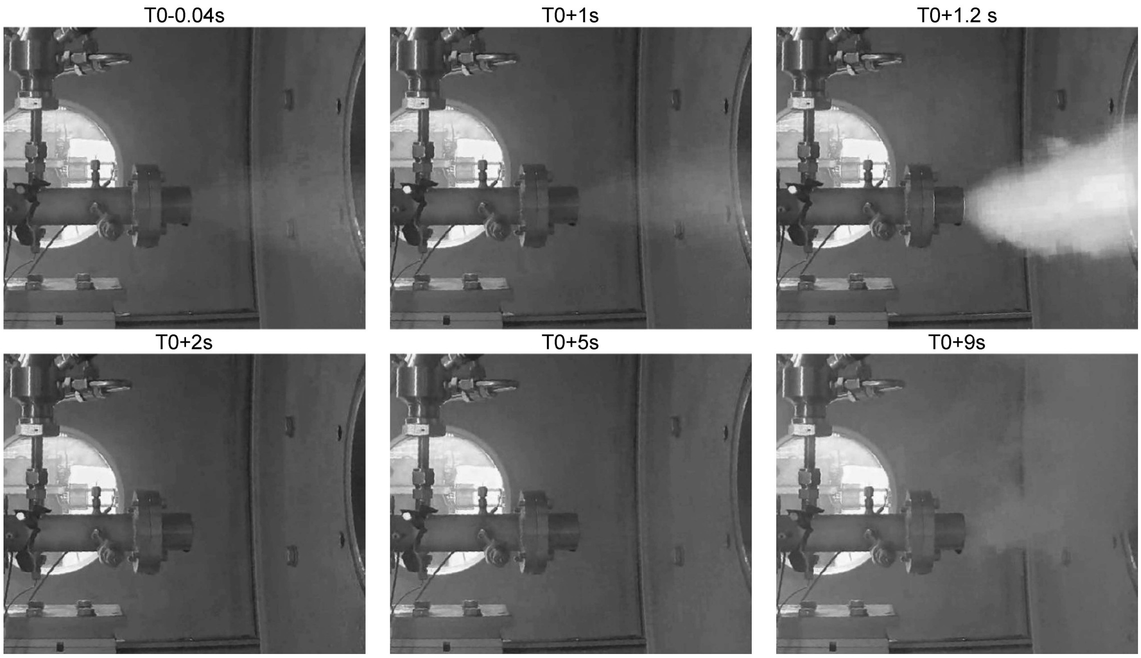

Figure 13. Frame shots of the test 214.

tially green flame the exhaust of the thruster were almost colorless. After shutdown white smoke, vaporized propellant, was produced.

4 Discussion

A green flame was observed in the test 028 conducted with the configuration Porous-A. Complete vaporization of the propellant was not achieved with this configuration. It should be noted that the tests conducted with thus configurations were conducted with a higher tank pressure (and therefore propellant mass flow rate) compared to the subsequent test. The heat accumulated from the porous material was not sufficient for vaporizing the propellant completely.

Configuration Porous-B was modified in order to increase the amount of heat transferred from the igniter to the porous material. The propellant flow rate was reduced. Combustion was observed with configuration Porous-B in the tests 081, 085 and 088. The combustion happened in three phases as shown in Figure 14. In the first phase a diffusion flame outside the combustion chamber was observed. Probably this flame was generated by the combustion of the volatile components of LMP-103S (methanol and possibly ammonia) which were vaporized from the torch igniter 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 takes part in the combustion process. 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 this 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 again observed. This was generated by the combustion of the volatile components of leftover propellant with atmospheric oxygen. These tests were conducted with the thruster in vertical position. This position facilitate the ignition and combustion as it maximize the heat feedback in the porous material and therefore in the fresh propellant. Interestingly no flame was observed when the tests were repeated with the thruster in horizontal position (test 106, 109, 110). A further explanation for the different behavior 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.

The configuration Porous-C was designed to achieve both complete vaporization of the propellant and having the hot combustion products from the torch directly in contact with the vaporized propellant. Combustion of FLP-106 was observed with this configuration in tests 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

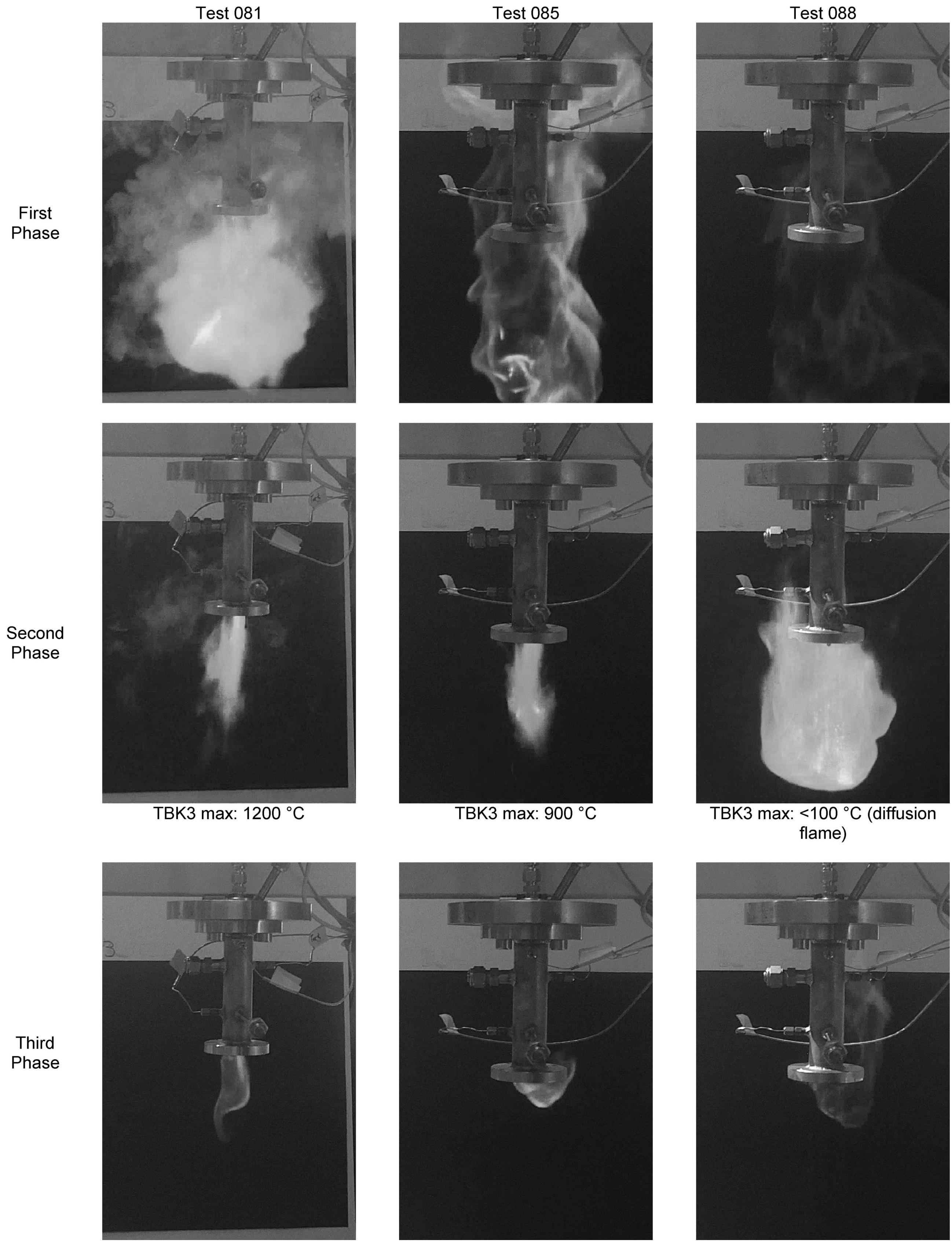

Figure 14. Phases of the combustion as observed with the configuration Porous-B.

was not achieved: the green flame disappeared shortly after the shutdown of the torch, when the FCV was still open. No flame was observed in the 2 tests conducted with configuration Porous-C and a nozzle (213 and 214). No tests with LMP-103S as propellant were conducted as the combustion chamber in configuration Porous-C was destroyed by an explosion during test 215.

5 Conclusion

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 color of the flame came from the copper inlay and the bronze porous material. 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 combustion of the propellant can be achieved when the gasified propellant was exposed 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 configurations tested enabled a sustained combustion under the used test conditions. 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.

An important result of the study is that it clearly indicates that thermal ignition of the two ADN-based propellants (LMP-103S and FLP-106) is achievable only when the propellants are vaporized, while ignition of the propellant in liquid form is not possible.

Acknowledgments

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References

[1] A. Larsson and N. Wingborg, "Green Propellants Based on Ammonium Dinitramide (ADN)", in *Advances in Spacecraft Technologies*, Jason Hall, Ed. IntechOpen, **2011**.

[2] Z. Yao, W. Zhang, M. Wang, J. Chen, and Y. Shen, "The Experimental Investigation and On-Orbit Flying Validation of the ADN-Based Liquid Thruster, presented at the Space Propulsion Conference", Seville, Spain, **2018**.

[3] CubeSat Propulsion 'EPSS' – Green Chemical Propulsion System, *NanoAvionics.* [Online]. Available: https://n-avionics.com/subsystems/cubesat-green-chemical-propulsion-system-epss/. [Accessed: 26-Jun-2019].

[4] 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, **2011**.

[5] P. Friedhoff, K. Anflo, P. Thormahlen, and M. Persson, "Growing Constellation of Ammonium Dinitramide (ADN) Based High Performance Green Propulsion (HPGP) Systems", presented at the 54th AIAA/SAE/ASEE Joint Propulsion Conference, Cincinnati, OH, **2018**.

[6] M. Negri, M. Wilhelm, C. Hendrich, N. Wingborg, L. Gediminas, L. Adelöw, C. Maleix, P. Chabernaud, R. Brahmi, R. Beauchet, Y. Batonneau, C. Kappenstein, R.-J. Koopmans, S. Schuh, T. Bartok, C. Scharlemann, U. Gotzig, M. Schwentenwein, "New technologies for ammonium dinitramide based monopropellant thrusters – The project RHEFORM", *Acta Astronaut.* **2018**,*143*, 105–117

[7] M. Negri, M. Wilhelm, and C. Hendrich, "Development of ADN-based Thruster Technologies – An overview of the European Project Rheform", presented at the 54th AIAA/SAE/ASEE Joint Propulsion Conference, Cincinnati, Ohio, **2018**.

[8] 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", presented at the 27th Conference on Small Satellites, **2013**.

[9] Monopropellant Thrusters Data Sheet, *Aerojet Website*, **2006**. [Online]. Available: https://www.rocket.com/files/aerojet/documents/Capabilities/PDFs/Monopropellant Data Sheets.pdf. [Accessed: 26-Jun-2019].

[10] M. Wilhelm, M. Negri, H. Ciezki, and S. Schlechtriem, "Preliminary tests on thermal ignition of ADN-based liquid monopropellants", *Acta Astronaut.* **2019**,*158*, 388–396.

[11] M. Negri, M. Wilhelm, C. Hendrich, N. Wingborg, L. Gediminas, and L. Adelöw, "Technology development for ADN-based green monopropellant thrusters: an overview of the Rheform project", presented at the 7th EUCASS, Milan, IT, **2017**.

[12] A. Dinardi, "High Performance Green Propulsion (HPGP)", ECAPS Report, 2013.

[13] M. Wurdak, F. Strauss, L. Werling, H. K. Ciezki, D. Greuel, R. Lechler, N. Wingborg, D. Hasan, C. Scharlemann, "Determination of Fluid Properties of the Green Propellant FLP-106 and Related Material and Component Testing with Regard to Applications in Space Missions", presented at the Space Propulsion, Bordeaux, **2012**.

[14] C. Maleix, P. Chabernaud, M. Artault, R. Brahmi, R. Beauchet, Y. Batonneau, C. Kappenstein, "Development and activity assessment of new catalytic materials for decomposition of ADN-based monopropellants", in *53rd AIAA/SAE/ASEE Joint Propulsion Conference*, Atlanta, GA, **2017**.

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