Development of a Green Bi-Propellant Hydrogen Peroxide Thruster for Attitude Control on Satellites

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Abstract
This document describes the selection assessment of propellants for a 1N bi-propellant thruster for attitude control on satellites. The development of this thruster is conducted in the frame of the project GRASP (Green Advanced Space Propellants) within the European FP7 research programme. The green propellant combinations H_2O_2 (87.5%wt) with Kerosene or H_2O_2 (87.5%wt) with Ethanol have been identified as interesting candidates and have been investigated in detail with the help of experimental combustion chambers at Fotec. Based on the obtained results a final assessment for one of the propellant combinations was performed.

1. Introduction

Green Propellants for satellite propulsion systems have achieved great interest in the European space industry. In comparison to the currently used storable, Hydrazine based propellants they offer a significant reduction of toxicity and hazard levels.

Increasing reservations and restrictions against production, transportation and in general ground handling of toxic propellants have surfaced recently (see [4]). During the past years a continuous reduction of acceptable threshold levels of ppm-concentrations of Hydrazine vapors in typical working environments has been forced upon the relevant industries by governmental health organizations. In several publications and studies performed by the space propulsion industry and the European Space Agency it was outlined that the handling and manipulation of toxic propellants on ground (e.g. on test benches and space craft pre-launch preparation facilities) are an increasing cost and time factor which has to be accounted for during the planning of satellite projects. It is a common opinion, that the transition to Green Propellants would bring for the near future a high economic benefit for the space industry - despite the fact that a new technology has to be introduced and qualified (see [5] for additional information).

Green propellants for in-space propulsion (orbital insertion and control as well as attitude control) are currently intensively investigated in the frame of the project GRASP (Green Advanced Space Propulsion) within the European FP7 research programme (see [1]). In this project Fotec proposes a bi-propellant thruster concept which is based on the utilization of highly concentrated and stabilized Hydrogen Peroxide (87.5%wt solution) in combination with Kerosene or Ethanol. A thrust level of 1N was selected as baseline with the purpose to provide precise pulse bits for attitude control, which means pulse-mode capability is an important key-feature. With this concept specific impulses in the range of Isp=300s are envisioned and a green alternative to the state-of-the-art bi-propellant thrusters, based on the storable and also highly toxic and hazardous propellants MMH and NTO shall be provided (see [2] and [3] for detailed information). Another important development goal is blow-down mode capability. Satellite propulsion systems with blow-down mode architecture require thrusters which are capable to be operated over a large range of system / combustion chamber pressures and also over a large domain of mixture ratio shifts. The thruster concept shall permit operation in bi-propellant as well as mono-propellant mode.

2. Bi-Propellant Thruster Concept

The main functional items and the principle of the Fotec 1N thruster concept are depicted in the following Figure 1:

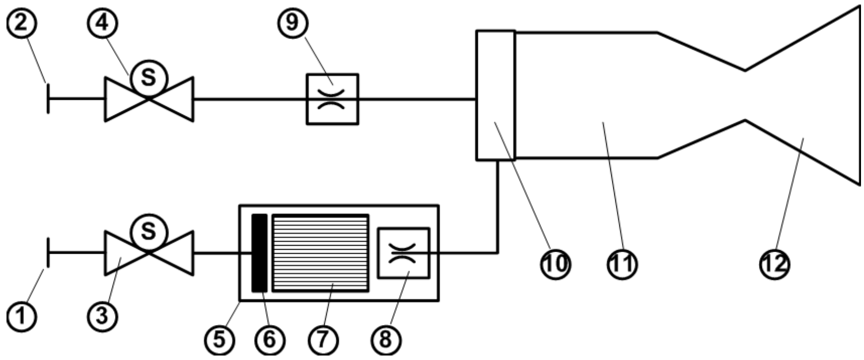

Figure 1: Green 1N bi-propellant thruster concept based on highly concentrated Hydrogen Peroxide (87.5%)

Pos. 1 and Pos. 2 are the fluidic interfaces to the propellant feeding system for Hydrogen Peroxide and Kerosene/Ethanol. Pos. 3 and Pos. 4 represent the Flow Control Valves of Hydrogen Peroxide and Fuel, respectively. Pos. 5 depicts the decomposition or catalyst chamber. Pos. 6 represents the Hydrogen Peroxide injector which is responsible for a uniform charging of the catalyst (Pos.7) where the catalytic decomposition of Hydrogen Peroxide occurs. Pos. 8 is a trimming device, necessary to adjust the flow of the decomposed H2O2 and the required interface conditions for the bi-propellant thruster injector (Pos. 10). The fuel flow is adjusted (for stationary and transient operational phases of the thruster) with the help of the trimming device (Pos. 9). The injector head with the main components manifold and injector (Pos. 10) is responsible for homogenous distribution of propellant components prior injection, has to provide a certain defined pressure differential via the injector in order to decouple the fluidic system from combustion chamber pressure fluctuations and adjusts the required injection velocities, momentum ratios, in order to achieve optimal atomization, mixing and evaporation of the propellants prior combustion in the combustion chamber (Pos. 11). The combustion of the propellant mixture is initiated by auto-ignition, which means, the Hydrogen Peroxide flow is activated prior the fuel flow in order to generate certain auto-ignition conditions (pre-ignition chamber pressures and temperatures) in the chamber (Pos.11). The combustion gases are expanded in the nozzle extension (Pos.12).

3. Elegant Bread Board (EBB) Unit and Test Facility

The key components and functional items (described in Figure 1) have been analysed analytically and are now implemented into an Elegant Bread Board model which shall represent the 1N bi-propellant thruster proposed in this work. In order to be able to investigate the performance in stationary conditions, a Nitrogen gas cooled combustion chamber design was selected (Figure 2). Due to the modular design of the EBB thruster unit it was possible to test various modifications of the bi-propellant injector, catalysts and decomposition chamber configurations. The implemented sensors necessary for the evaluation of the thruster performance can also be seen in Figure 2.

Figure 3 depicts the functional groups of the bi-propellant test facility: Hydrogen Peroxide storage tank and feeding system, Kerosene / Ethanol storage tank and feeding system as well as the measurement and control system. In order to be able to perform experimental investigations and evaluation of thruster technologies under representative conditions, the propellant system of the bi-propellant test bench was similar designed to a satellite propulsion system with similar integrated fluidic components (standard industrial) and representative mass flows and system pressures.

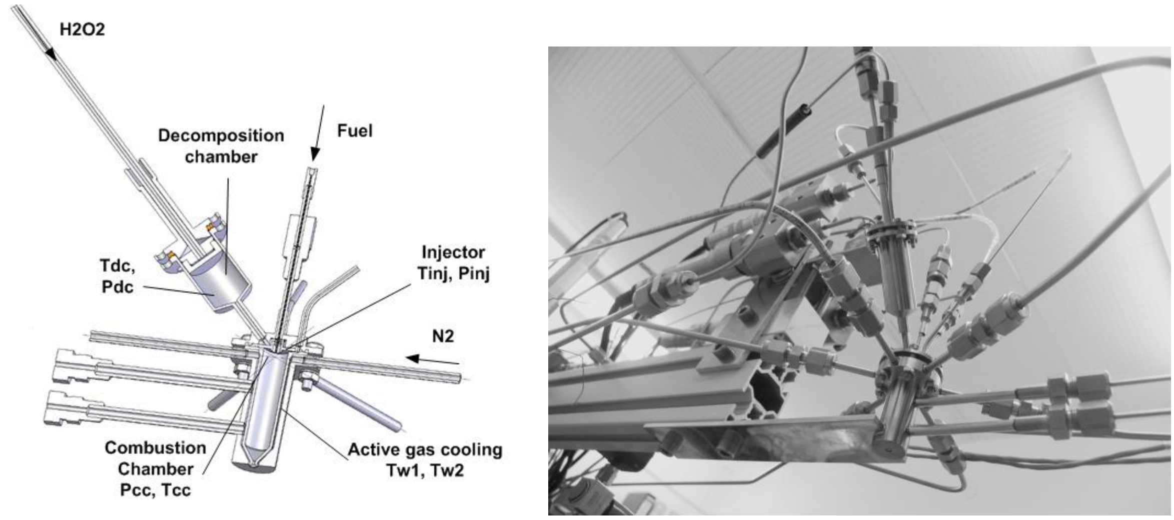

Figure 2: Elegant Bread Board thruster model

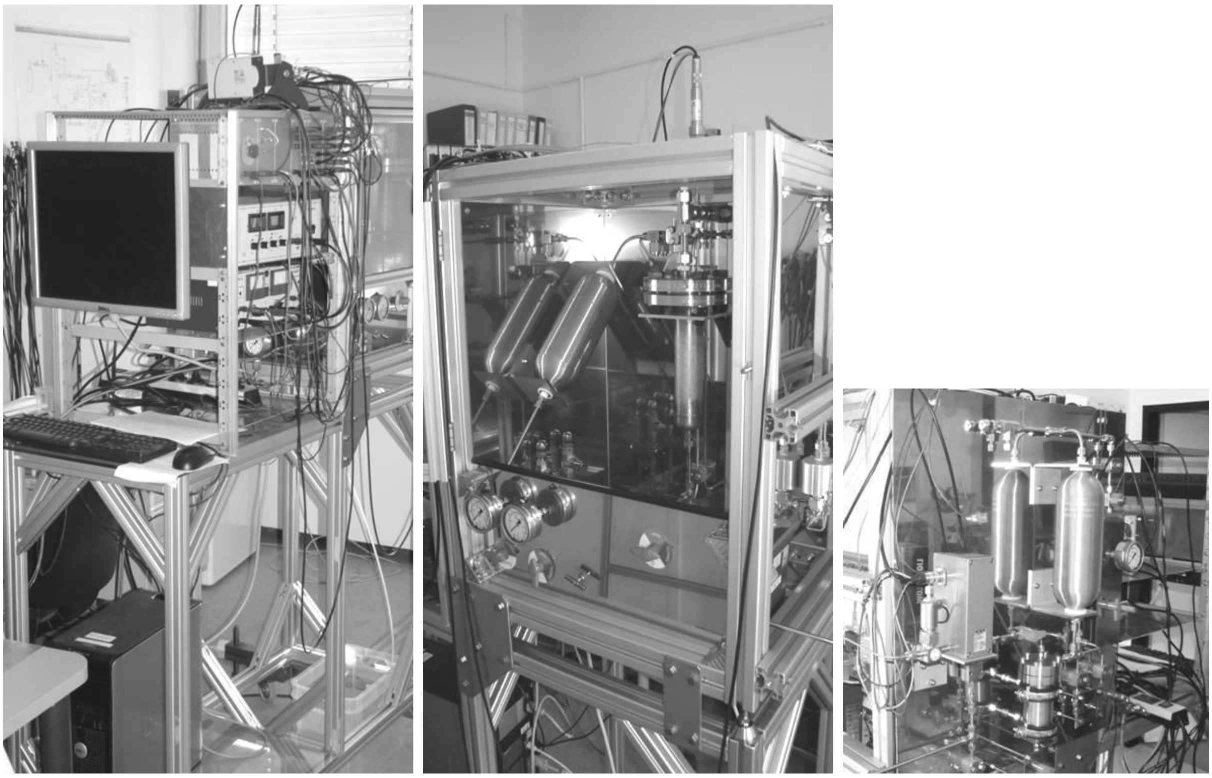

Figure 3: Bi-propellant test facility: control panel (left), H2O2 fluidic system (center), Ethanol/Kerosene fluidic system (right)

4. Experimental Results

Hot firing tests have been performed with both propellant combinations H_2O_2/Kerosene and H_2O_2/Ethanol. The main purpose was the evaluation of the bi-propellant injector performances under various test conditions during transient start-up phases and also stationary operation of the thruster with the two fuel candidates: Kerosene and Ethanol. One additional important point to investigate in detail is the auto-ignition behaviour of mixtures of the proposed propellants. Also the decomposition performances of proposed catalyst configurations have been experimentally verified.

4.1 EBB Hot Firing Tests

The following Figure 4 depicts raw data obtained during a hot firing test from the allocated pressure sensor positions in the EBB experimental combustion chamber. An example of the pressure-time traces for the successful ignition and firing of H_2O_2/Kerosene (Figure 4, left) and H_2O_2/Ethanol (Figure 4, right) are shown. As can be seen from the diagrams, auto-ignition was detected (after the valve open command) by a sudden rise of the combustion chamber pressure Pcc (see also Figure 2) and also by the thermocouples Tw1 and Tw2, with which the combustion chamber wall temperatures have been monitored. The corresponding pre-ignition pressures and temperatures have been adjusted by certain tank pressure settings and pre-heating durations (in mono-propellant mode) respectively. With this strategy a systematic pre-ignition pressure-temperature screening has been performed. Figure 5 summarizes the results obtained from the auto-ignition studies. The diagram on the left side shows the auto-ignition limits obtained from the EBB tests using H_2O_2/Kerosene as propellant combination. Already available test data points from [6] are included as additional information. With the newly developed EBB thruster it was now also possible to investigate the ignitability of Ethanol in decomposed Hydrogen Peroxide. Test results are depicted in the right side of Figure 5.

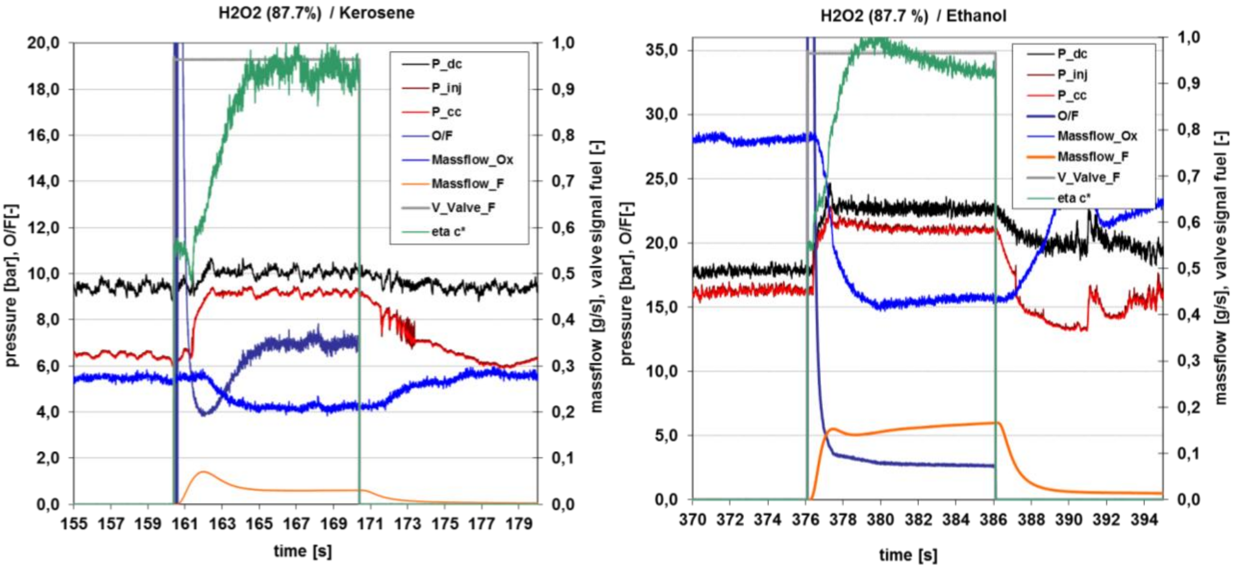

Figure 4: Hot firing test pressure and mass flow measurements

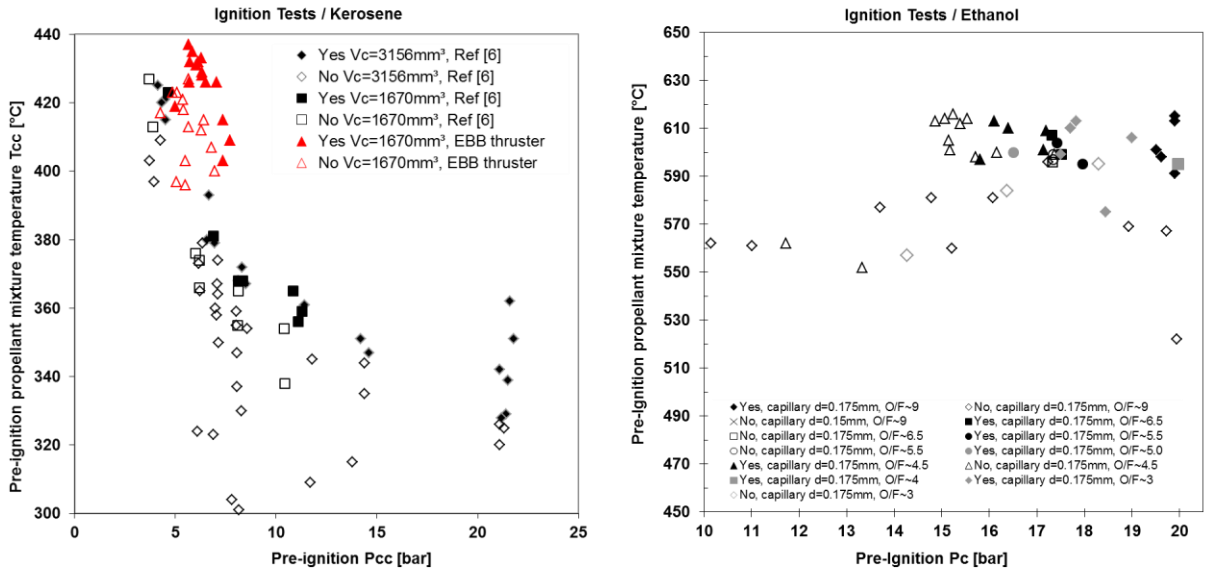

Figure 5: Evaluation of necessary auto-ignition conditions of propellant mixtures

From the above Figure 5 and Figure 6 it can be clearly observed that significantly higher ignition pressures and higher ignition temperatures are needed when using Ethanol as fuel. The tests have been performed with identical chamber dimensions but slightly different injector geometries for the two propellant combinations. The error bars included into the sub-sequent diagrams shall represent the accuracy, provided by the currently used measurement system.

With the EBB thruster hot firing tests a systematic assessment of the performance or behaviour during stationary hot firing was performed. Figure 6 summarizes the obtained performance data points from stationary hot firings (left side: H_2O_2/Kerosene, right side: H_2O_2/Ethanol) as function of tested mixture ratios O/F at nearly constant chamber pressures P_{cc}. The parameter $c^*_{exp}=P_{cc}*A_{th}/m_p$ is the characteristic value obtained from direct pressure P_{cc} and propellant mass flow m_p measurements. The parameter c^*_{theory} is a calculated characteristic velocity (CAE GordonMcBride, see [7]) using the theoretical decomposition temperature of Hydrogen Peroxide and actual mixture ratios from the tests as input.

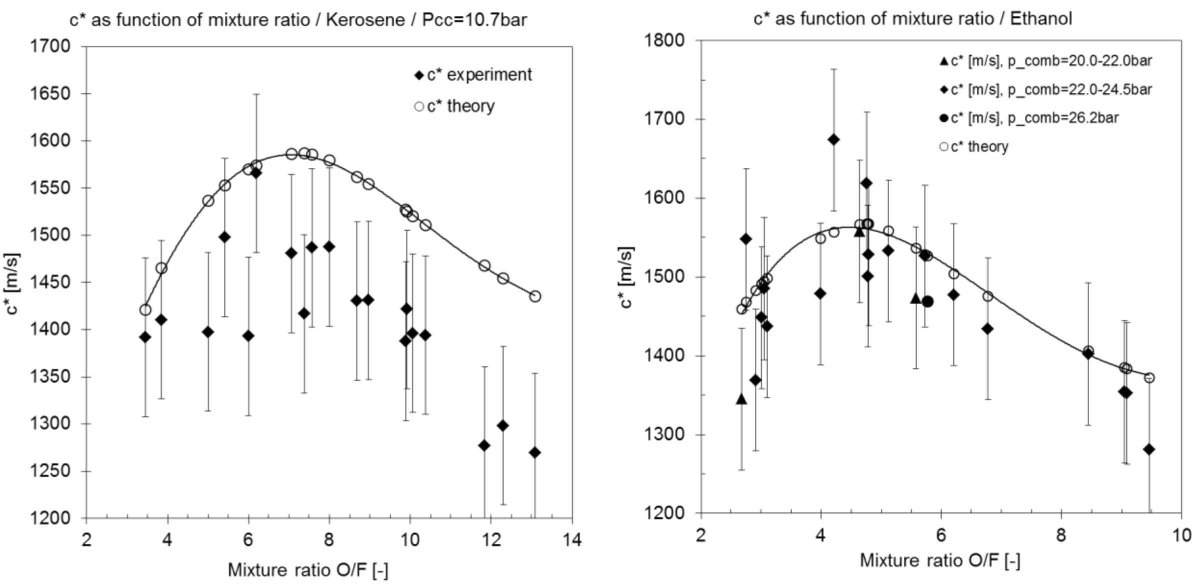

Figure 6: Thruster performance as function of mixture ratio – c* evaluation

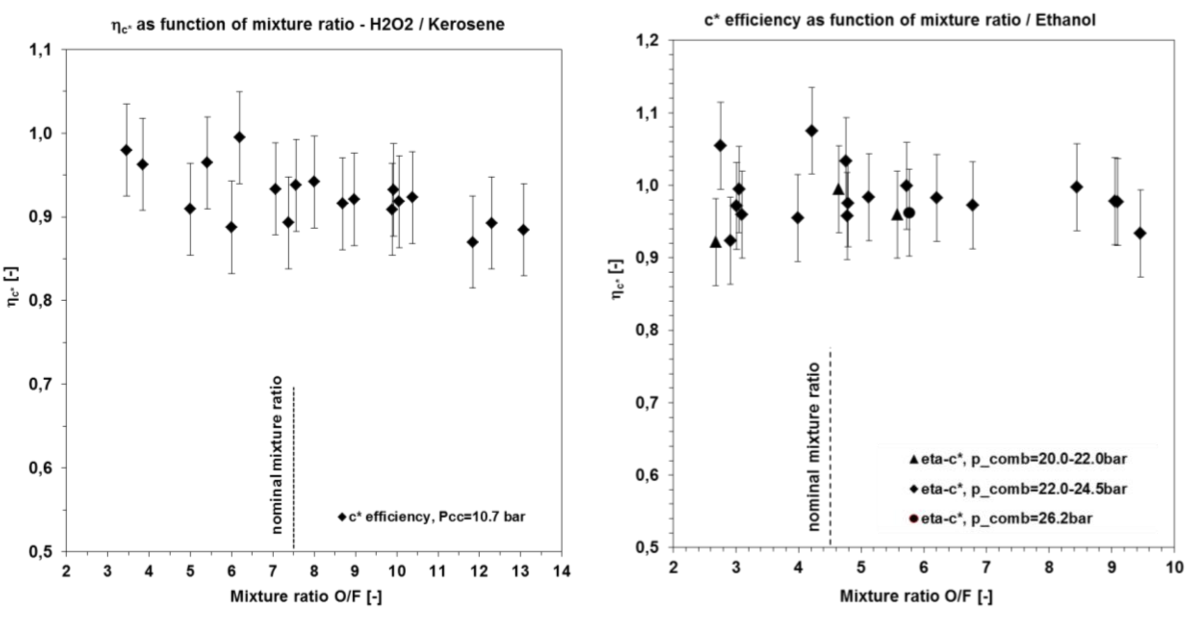

Figure 7: Thruster performance as function of mixture ratio – η_{c*} evaluation

As can be seen from Figure 6, the experimental data points show a qualitative behaviour of the c* values as function of the mixture ratio O/F similar to theoretical characteristic velocities, calculated with [7]. Careful treatment of the absolute values for characteristic velocities c* and combustion efficiencies η_{c*} has to be taken into account: in reference [8] the problematic evaluation of c* in the case of thrusters with small dimensions (especially throat diameters – in our case A_{th}< 1mm) is discussed. Whereas in the case of larger dimensions the characteristic velocity c* can be provided with acceptable accuracies, in smaller dimensions, finite boundary layer thicknesses and therefore blocking effects, which significantly influence presumed throat dimensions A_{th}, need to be considered. What can be obtained as an important result from this study, is the demonstration of the in-sensitiveness of combustion efficiency η_{c*} from the mixture ratio O/F. As it can be seen from Figure 7, for both propellant combinations no significant decay of performance was observed over the tested range, indicating that the selected injection principle is able to cope with large O/F variations.

Another major aspect for the demonstration of blow-down mode capability was the evaluation of thruster performance as function of the combustion chamber pressure P_{cc}. Test have been performed at nearly nominal mixture ratios.

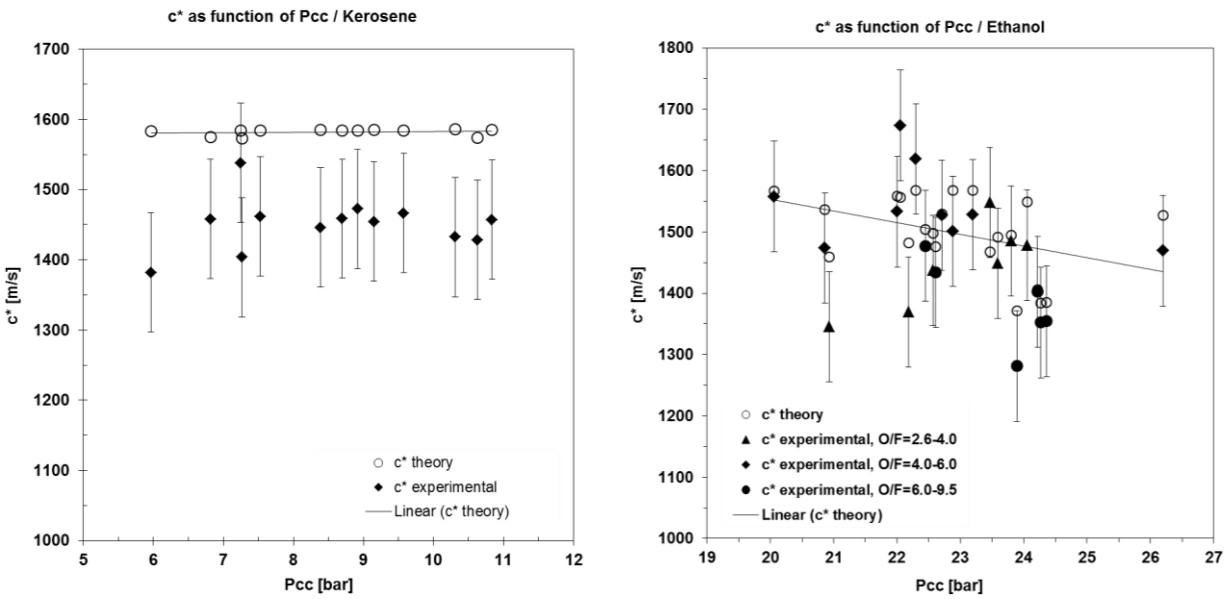

Figure 8: Thruster performance as function of chamber pressure – c* evaluation

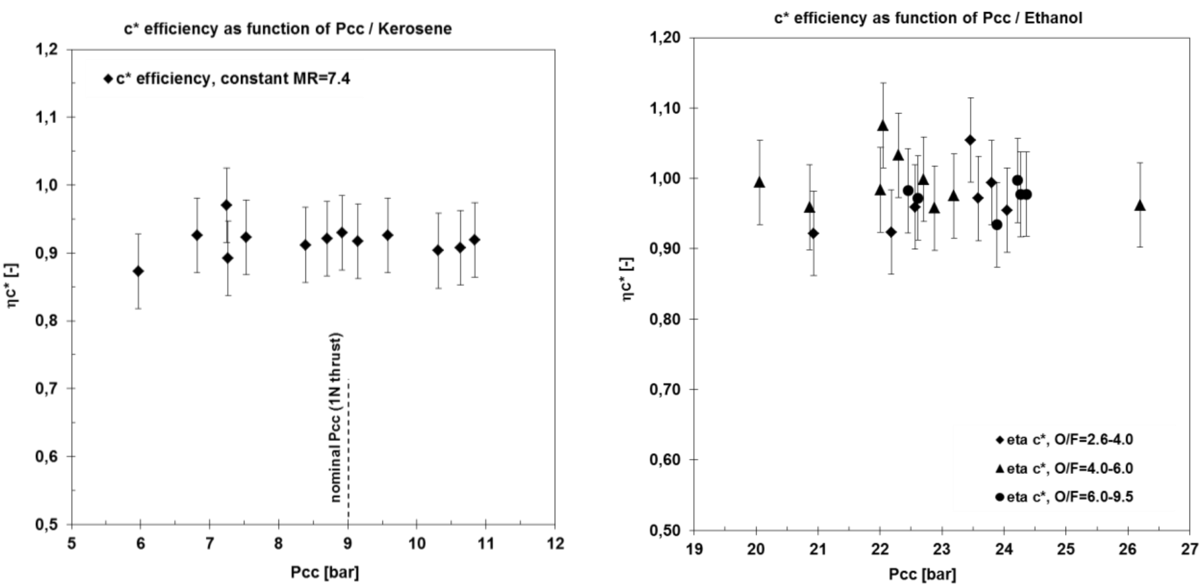

Figure 9: Thruster performance as function of chamber pressure – η_{c*} evaluation

Figure 8 and Figure 9 depict experimental c* and η_{c*} values over the tested pressure ranges for both propellant combinations. From the test results it can be concluded that the obtained characteristic velocities and combustion efficiencies seem to be independent from the adjusted system and therefore chamber pressures P_{cc}. These test results confirm the selected bi-propellant injection principle for the envisioned application of the thruster.

Absolute values need to be interpreted very carefully (see [8]). For the next development phase a direct measurement is proposed, which is according [8] more precise than c* evaluation (especially for small thrusters).

4.2 Catalyst and Decomposition Chamber Tests

The catalyst and the decomposition chamber are the key-components which determine the transient behaviour and the maximum operational life of the bi-propellant thruster. Therefore, a significant effort in the catalyst development was conducted by Fotec. Lowest possible transition times, a high degree of reproducibility concerning pulse-to-pulse behaviour for a catalyst and between different samples of catalysts are a major research topic. A highly efficient decomposition of large quantities of Hydrogen Peroxide with a huge number of cold starts is required for the operation of the bi-propellant thruster during the operational life. Exemplarily, Figure 10 shows the temperature-time traces of selected catalyst configurations tested at Fotec with the EBB configuration in mono-propellant mode (decomposition of 87.7% H_2O_2) – measured with the sensor T_{dc}, which is located directly downstream of the catalyst (see Figure 2).

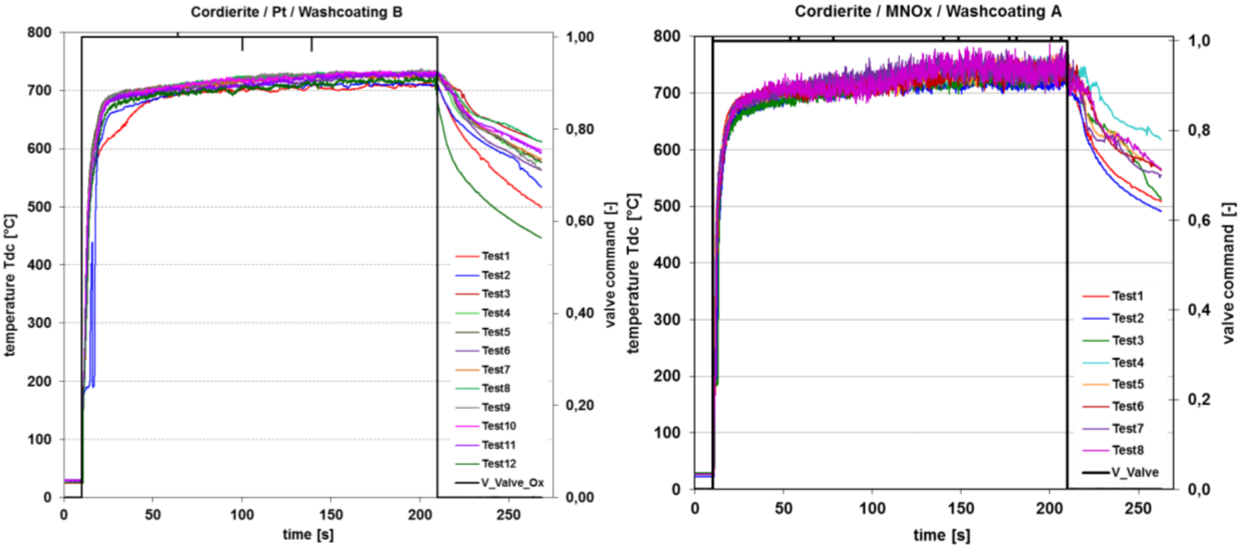

Figure 10: Catalyst and decomposition chamber tests

One important topic is the provision of cold-start capability of the catalyst and therefore also for the bi-propellant thruster. That means thruster start-up shall be possible without any additional heating devices which pre-heat the catalyst to a certain temperature level. Less complexity of the thruster system (cost aspect); reduced electrical power consumption and gained flexibility concerning thruster operation (no waiting times for pre-heating have to be considered) would be the benefit. Dedicated cold-start tests have been performed in order to critically assess the cold-start capability in a low temperature environment. Figure 11 shows the temperature-time traces with the temperature sensors allocated in the EBB thruster (see also Figure 2). Reliable and efficient decomposition has been demonstrated for temperatures in the near vicinity of T=0°C.

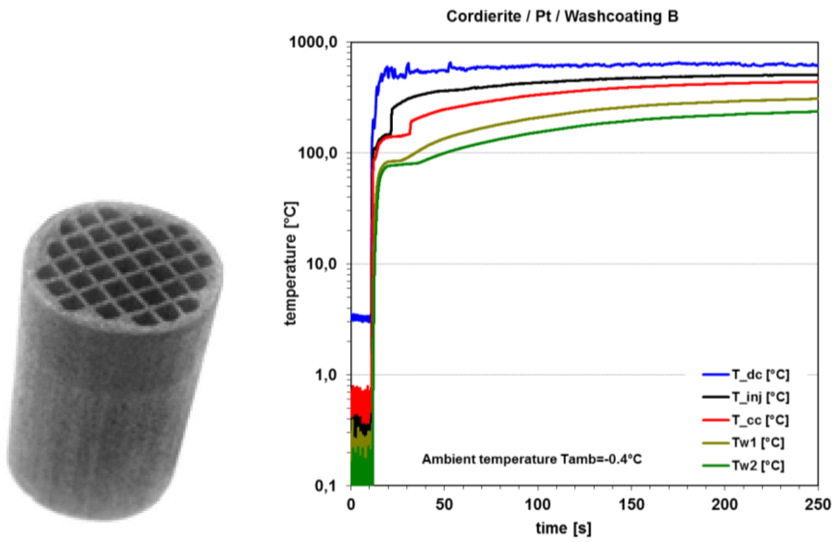

Figure 11: Monolith catalyst configuration and demonstration of cold start capability

5. Propellant Assessment

The propellant combinations Hydrogen Peroxide/Kerosene and Hydrogen Peroxide/Ethanol have been tested with the EBB thruster unit. In the following the results for both propellant combinations are summarized and compared:

- Both propellant combinations showed a reliable ignitability during the EBB thruster tests with using decomposed Hydrogen Peroxide (87.5%wt) as oxidizer
- With both propellants a large domain of stationary chamber pressures and mixture ratios has been successfully tested
- With the usage of Kerosene as fuel a significant reduction of the necessary pre-ignition pressures (lowest: P=4.7bar, highest: P=22bar) and temperatures (T=330–450°C) has been achieved in comparison to Ethanol (lowest: P=16bar, highest: P=20bar) with temperatures (T=580-615°C)
- With the selection of Kerosene a larger margin between necessary pre-ignition temperatures and theoretical decomposition temperatures is provided (especially if the catalyst loses performance at end of life)
- Due to the fact that lower pre-ignition temperatures are necessary for Hydrogen Peroxide with Kerosene, also less time delays are expected during start up to reach auto-ignition conditions
- Hydrogen Peroxide / Kerosene provide due to the lower required minimum pre-ignition pressures the possibility to adjust the nominal thrust levels at lower stationary combustion chamber pressures. This causes a significant reduction of the thermal loading of the thrust chamber wall structure, due to the pressure dependency of the hot gas side heat transfer coefficients α_{hg} which can described by $\alpha_{hg} \sim Pc^{0.8}$
- Due to the fact that with Kerosene as fuel component lower chamber pressures have been achieved, larger blow-down ratios BR than Ethanol can be realized (Kerosene: BR<4.5, Ethanol: BR<1.5). This would promote the implementation of the 1N thruster concept into satellite propulsion systems with blow-down mode architecture
- During the general assessment of green propellants (see [2]) it was shown that Kerosene provides slightly higher performances and due to the higher mixture ratio also a higher impulse density
- The increased pre-ignition pressure levels (Pign > 16bar) when using Ethanol as propellant resulted in high values of combustion chamber pressures (Pcc > 25bar) and therefore also system pressure levels exceeding design pressures of off-the-shelf fluidic components (tanks, flow control valves, etc.)

One important result was the determination of a catalyst configuration which provides performances which are compliant to defined thruster requirements:

- It was demonstrated that with the monolith catalyst configurations highly efficient and reliable catalytic decomposition of Hydrogen Peroxide can be achieved without the implementation of any heating devices. Lowest tested structural initial and ambient temperatures have been in the near vicinity of T=0°C
- One important achievement during the evaluation of selected catalyst configurations was the demonstration of large accumulated Hydrogen Peroxide mass flows. 17.8 kg Hydrogen Peroxide have been decomposed with one catalyst. Being bold and comparing the achievements with already space qualified thrusters – with the same thrust level and which rely on the operation of catalytic reactors - this represents 75% of nominal values of the ECAPS 1N thruster [11] and 35% of the EADS CHT1 thruster [12]). In total 140 cold starts and an operational time of more than 8 hours have been accumulated

With this sum of arguments it was decided to use the propellant combination: Hydrogen Peroxide/Kerosene and the currently available catalyst design for the next development phase of the 1N bi-propellant thruster within GRASP.

6. Conclusion

Within the FP7 project GRASP (Green Advanced Space Propellants) a 1N bi-propellant thruster for attitude control on satellites, using the green propellant combinations H_2O_2 (87.5wt%) and a hydrocarbon fuel, is developed. Tests on an Elegant Bread Board (EBB) model, which allowed a detailed investigation of auto-ignition phenomena, stationary combustion and hot firing of the thrusters as well as the catalytic decomposition of Hydrogen Peroxide have been performed. On basis of the obtained test results a final selection of the propellants has been proposed. The propellant combination H_2O_2/Kerosene offered best performances with respect to defined thruster requirements and envisioned development targets.

In the working plan of the GRASP project the design and testing of an advanced development model thruster is a further milestone. With the help of this experimental combustion chamber the final selection of propellants as well as catalyst configuration will additionally be verified. One critical aspect is the time constants needed to reach stationary hot firing conditions. The EBB thruster unit was designed for maximum flexibility, maximum access of sensors, and provision of a high structural safety as well as an active cooling system (not flight representative). This resulted in high thermal masses and therefore large transient times. Therefore, one major development goal for the design of the development model is the implementation of flight representative chamber and nozzle materials and also cooling technology. The design and development process will be focused on structural and thermal optimization.

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