Design and study of quasi-hypergolic green propellant rocket engine

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Abstract
The paper describes the design process of an experimental, bipropellant rocket engine as well as the test campaign. The engine was built to study the ability of quasi – hypergolic ignition of decomposed, highly concentrated hydrogen peroxide with various liquid fuels. Utilization of this phenomenon is a promising alternative to strictly hypergolic, extremely toxic propellants that are currently in use for satellite thrusters. Presented engine was tested on kerosene, isopropyl alcohol and isooctane. The results of firings are described and compared herein. Apart from the engine construction itself, this paper also describes the test stand setup, and pressure fed system that was used for this research.

1. Introduction

There is a growing demand for green propellant engines, especially for the satellite thrusters, that are currently being run on toxic propellants such as hydrazine and its derivatives. It is not only caused by the increasing environmental restrictions (especially in the case of launch or development failure), but also by the fact that high costs of handling, including the level of production, qualification, shipping, and product development. However, the costs and hazards that are involved are being accepted due to great benefits offered by these propellants. A significant advantage of currently used propellants is their hypergolicity, that is ability to ignite when they come into contact. This phenomenon is especially important when there is a requirement of engine restartability - which is practically always a demand in the case of satellite thrusters. There are many works that are now being focused on replacements of presently used hypergolic, toxic propellants[3]. Also in Poland, at the Institute of Aviation (IoA), research aimed on development of green propellant rocket engine is currently underway. The main objective that has been accomplished to date was to establish the engine demonstrator[1] that, in the future, would be capable to replace strictly hypergolic systems. Very promising results, that were achieved pushed this work to the stage that is described in the current paper - new experimental unit was built, which modular form enables investigation of numerous phenomena that are related to the engine performance.

2. Engine design

Although different fuels have been tested with the presented engine, the design process was suited for utilization of isooctane. The engine was designed to generate vacuum thrust of 500N. Chamber pressure, Oxidizer to Fuel Ratio (OFR) and other engine parameters are summarized in the Table 1.

Table 1. Engine design specification

Quantity	Value	Unit
Vacuum thrust	500	N
Chamber pressure	10	bar
OFR	6	-
Ae/At	330	-
Catalytic bed loads	150	Kg/s/m2

The design process has been based on the results obtained during previous study[1] followed by optimization procedures. The engine is composed of two major parts – the catalytic chamber and the combustion chamber (Figure 1). Oxidizer, with flowrate limited by cavitating venturi, is delivered to the catalytic chamber where decomposition takes place instantaneously. High temperature decomposition products, that is gaseous oxygen and steam are then axially injected into the combustion chamber. Fuel, on the other hand, is introduced into this hot, high momentum stream – such configuration provides rapid atomization and evaporation of the fuel droplets. The ignition occurs, and the combustion products are then accelerated by the graphite nozzle. The latter element is easily changeable, thus different nozzle shapes can be studied.

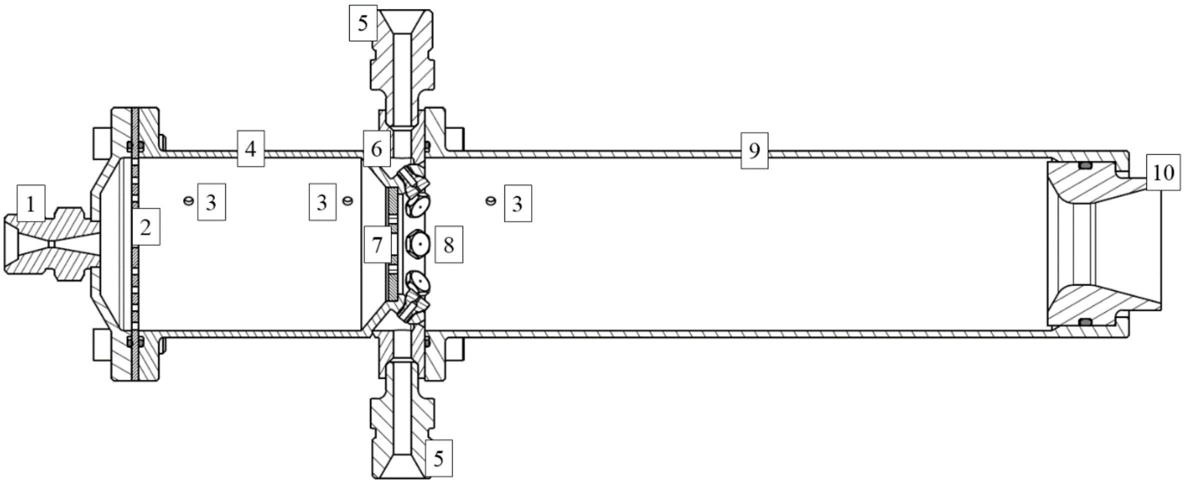

Figure 1. Engine cross section: 1-cavitating venturi, 2-HTP distributor, 3-measurement ports, 4-catalytic chamber, 5-fuel ports, 6-fuel collector, 7-HTP injector plate, 8-fuel injectors, 9-combustion chamber, 10-nozzle

For the test purposes, the engine is characterized with interchangeable injectors (Figure 2), which can be easily adjusted to investigate influence of injection velocity and pressure drop on the combustion efficiency.

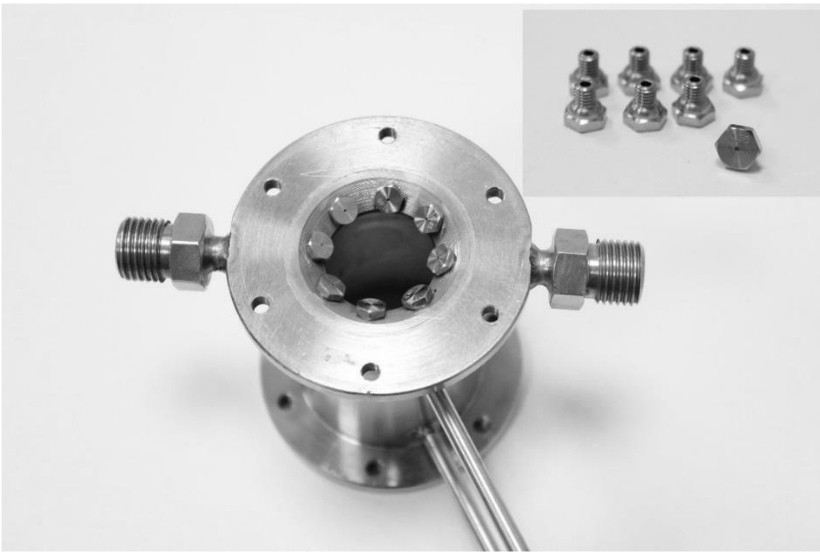

Figure 2. Catalyst chamber with interchangeable fuel injectors

The chamber wall thickness was minimized to withstand 3 seconds burning process in bipropellant mode. Although conducted tests focused on those relatively short time firings, design considerations for ablation insert have also been taken as such approach would increase the firing times above one minute. The primary objective of the optimization procedures was to confirm their propriety under experimental investigation. This is due to the fact that the engine will finally be made of more sophisticated structural materials. Although showing excellent results, current construction is still under development, and for cost minimization it is mainly manufactured of standard stainless steel, grade 316 (except the nozzle, which is made of graphite). There is ongoing work, leading to manufacturing the elements from state of the arts materials, including composites which will considerably lower the engine weight.

A presented design enables the measurement of pressure and temperature in crucial sections of the engine during firings. The measurement ports are located in five sections and enable measurements of temperature and pressure in the cavity upstream HTP distributor, and at the inlet and outlet of the catalytic chamber, as well as in the combustion chamber.

3. Propellants

For the test purposes, highly concentrated hydrogen peroxide (98%+ grade) was prepared in situ from widely available 60% solutions of reagent grade. Fractional vacuum distillation combined with purification process (Figure 3) conducted in the Laboratory of Chemical Propellants at IoA, allows to obtain HTP that meets military standard of MIL-PRF-16005F: Type 98, High Purity[2].

Figure 3. HTP installation, and storage[2].

As mentioned before, a few different fuel candidates have been chosen to be tested with 98%+ HTP with the presented engine. The choice was dictated by fuel availability (also price), performance, physical properties (including auto ignition temperature, which has significant influence on ignition delay times) and environmental friendliness. To the date, the tests have been successfully performed on:

- Kerosene
- Isooctane
- Isopropyl alcohol

Propellants performance, for chamber pressure p_c = 10 bar and nozzle expansion ratio ε = 330 in the form of Specific Impulse for tested fuels and HTP is presented in the Figure 4 below. These parameters are applied as reference from the rocket engine S-400-15 (I_{sp} = 321 s) [7], made by EADS Astrium and used on ARTEMIS satellites.

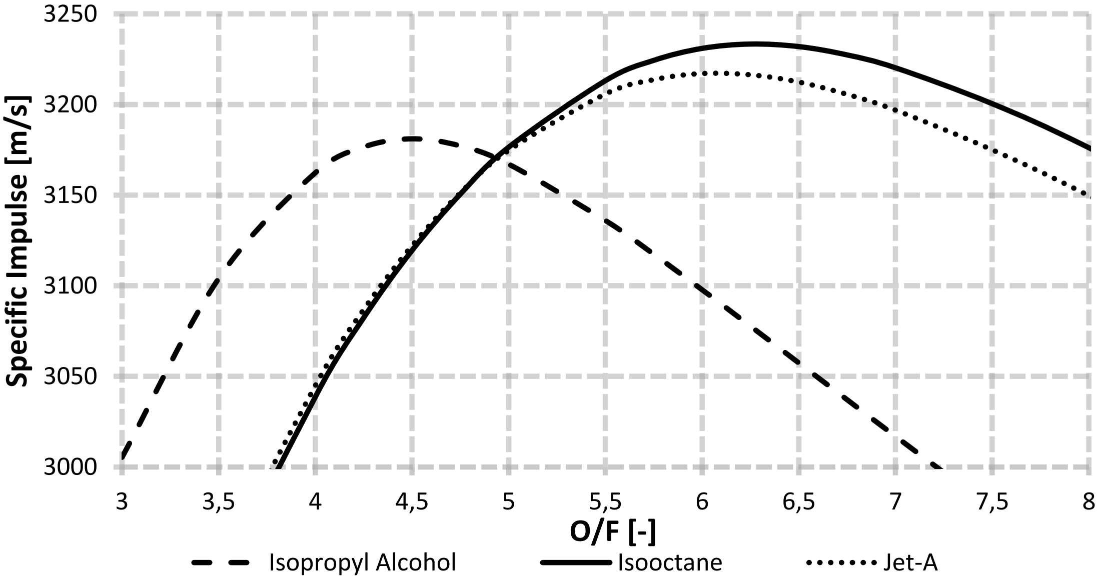

Figure 4. Theoretical specific impulse of fuels with 98%+ HTP, p_c=10bar, ε=330.

3.1 Propellant supply system

The pressure fed system shown in the Figure 5 was used to deliver both oxidizer and fuel to the engine.

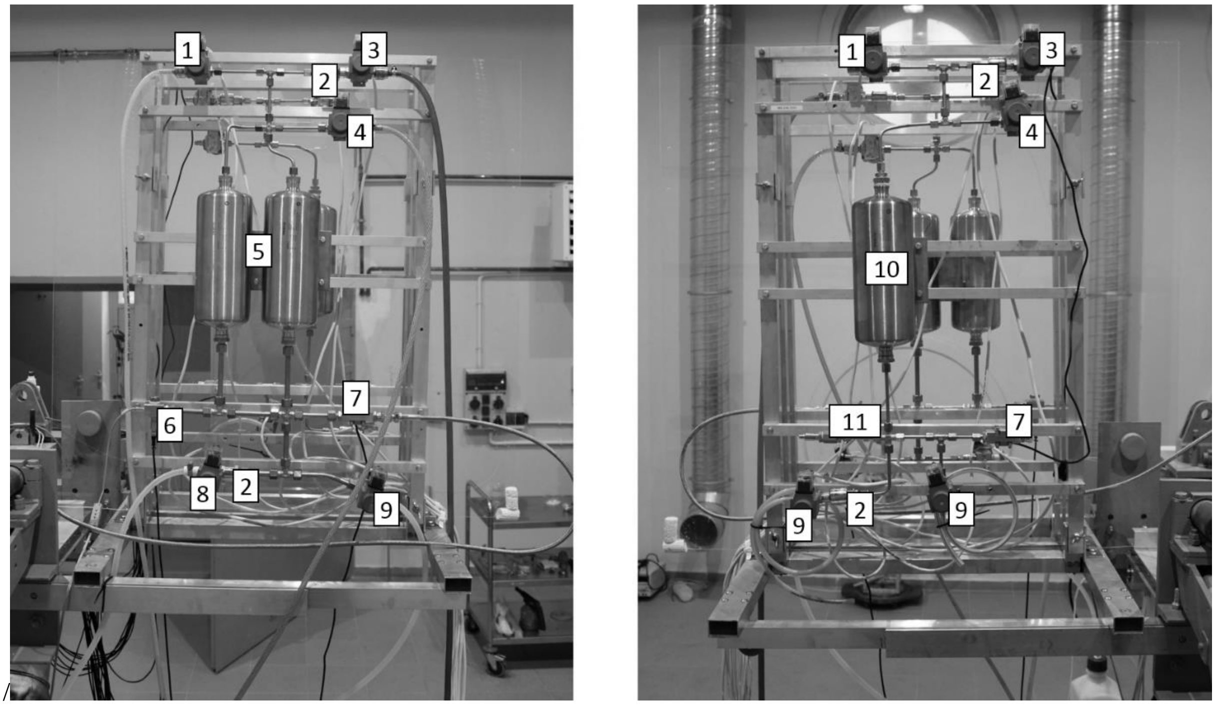

Figure 5. Propellant supply system: HTP (left) and fuel (right). 1-vacuum line valve, 2-check valve, 3-pressurizant valve, 4-relief valve, 5-HTP tanks, 6-pressure and temperature measurement port, 7-flowmeter, 8-inlet valve, 9-dump valve, 10-fuel tank, 11-pressure measurement port.

The system utilizes gaseous nitrogen as pressurizing agent, and is a standard construction used to store (during the tests) and deliver propellants for different propulsion units under investigation. This includes hybrid motors, and monopropellant thrusters, that have been tested at IoA so far. In order to reduce the costs, standard industrial solenoid valves were utilized to control the flow, although special care was taken to choose fully compatible with the propellants products. The valves used are characterized by opening times of the order of 20ms (for the fuel) and 25ms (for the oxidizer). However, the exact opening times are planned to be precisely estimated (experimentally) in the nearest future. The system can be operated remotely (including tanks filling), thus minimizing the hazards.

4. Catalysts

Similarly to 98%+ HTP, the decomposition catalysts for HTP have also been prepared at IoA. The catalyst chosen for a current study is a result of the previous work under PECS Programme (Plan for European Cooperating States), entitled *Research on the composite catalyst bed for decomposition of hydrogen peroxide to be applied in a monopropellant thruster* [2]. Over fifty catalyst were prepared and tested in order to select an efficient one suitable for decomposition of 98%+ hydrogen peroxide during that research.
The current study utilises a kind of composite catalyst, also known as a structure catalyst (Figure 6).

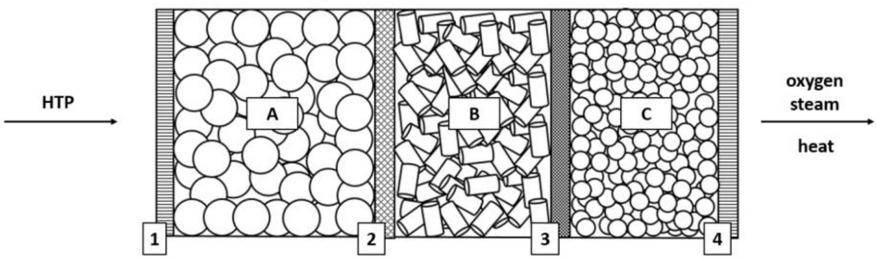

Figure 6. Composite catalyst arrangement. 1- HTP distribution plate; 2,3-mesh wires; 4-decomposition products injector (to the combustion chamber); A,B,C – various catalysts

5. Data acquisition system

As it was mentioned in chapter 2, working pressure and temperature were measured in five engine sections. For that purpose KELLER PA-21 PY pressure transducers, which allows pressure measurements in the range of 0…40bars with total error of ±0.5FS (at room temperature) were used. The standard thermocouples of type K were utilized to perform the temperature measurements. The thrust level was measured with the use of Wobit KTB52 2410 0-500N (total error 0.2%FS) tensometric force sensor. In Figure 7 the sensors arrangement is presented. The picture also shows the engine on the test stand before hot firing.

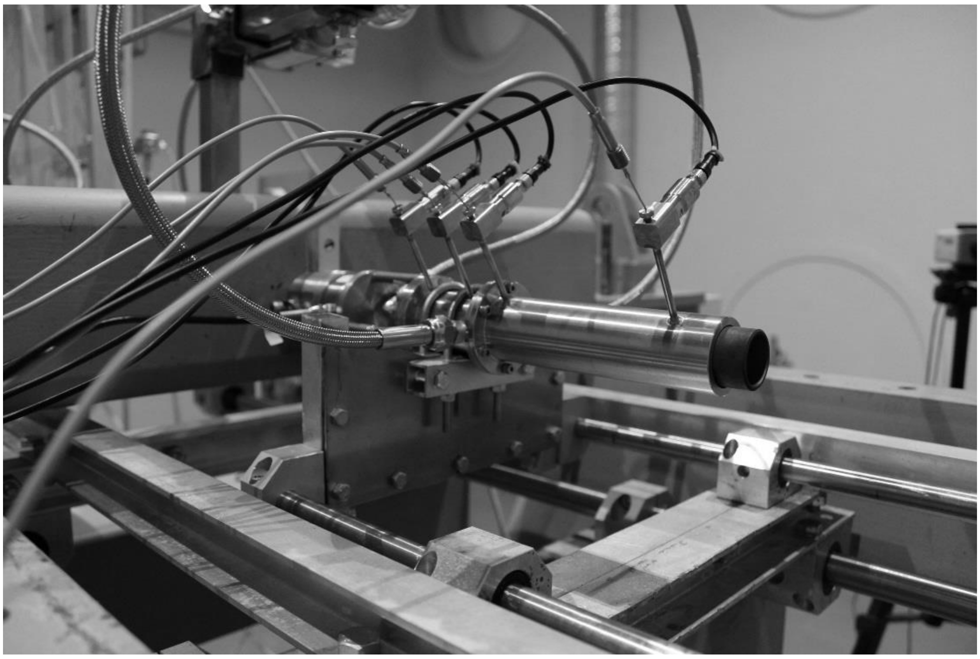

Figure 7. Engine on the test stand

Apart from the engine parameters, propellant pressure was also measured in the storage tanks (Figure 5). Due to the safety reasons, 98%+ HTP installation was additionally equipped with thermocouple to control the risk of potential decomposition, which would harm the installation (although no such undesirable case has been observed at IoA so far).
The data was collected with the use of National Instruments data acquisition card, model NI USB-6259. Although the sampling frequency was set at 10 kHz, the actual measurement frequency was limited by the sensors and was 2kHz, 1kHz, and 200 Hz for pressure, thrust, and temperature measurements respectively. The data acquisition card was also used as the control unit. It allowed remote filling of HTP tanks (previously evacuated to the vacuum conditions), by the adequate sequence of the valves openings. Also the main fuel and oxidizer valves, thus engine operation, was controlled remotely according to previously set procedure.

6. Experimental results

Quasi-hypergolic staged combustion is based on the heat released in the process of hydrogen peroxide decomposition as the source of energy for fuel ignition. Taking this into account, the temperature measured in the catalyst chamber outlet section is very important parameter considering the process of fuel ignition delay time. For 98% concentrated HTP the adiabatic decomposition temperature of the gaseous products may be calculated as 962^{o}C. Thus, the measurements of pressure and flow temperature at inlet and outlet sections of the catalyst chamber gives a useful information about the HTP decomposition efficiency.
A heterogeneous catalyst bed configurations utilized aluminum oxide (Al_2O_3) catalyst support with manganese oxides and additional compounds, including samarium and lanthanum, as the active phase[5].Such catalyst have been used during all of the performed tests.
This combustion initiation method, proposed for fuels without any additional promoters (e.g. catalyst dissolved in fuel), was tested at Space Technology Department for kerosene (Figure 8 and Figure 9), isooctane (Figure 10) and isopropyl alcohol (Figure 11).

The tests of kerosene injection into decomposed HP flow, the fuel valve opening was executed 0.5 - 1 second after oxidizer flow initiation. The chamber pressures between 2 and 10 bar were recorded during firings, what is complementary to Sadov's research [6]. A different injector-head configuration – 4 or 8 injectors – have been used and various autoignition sequences were observed in the performed tests.

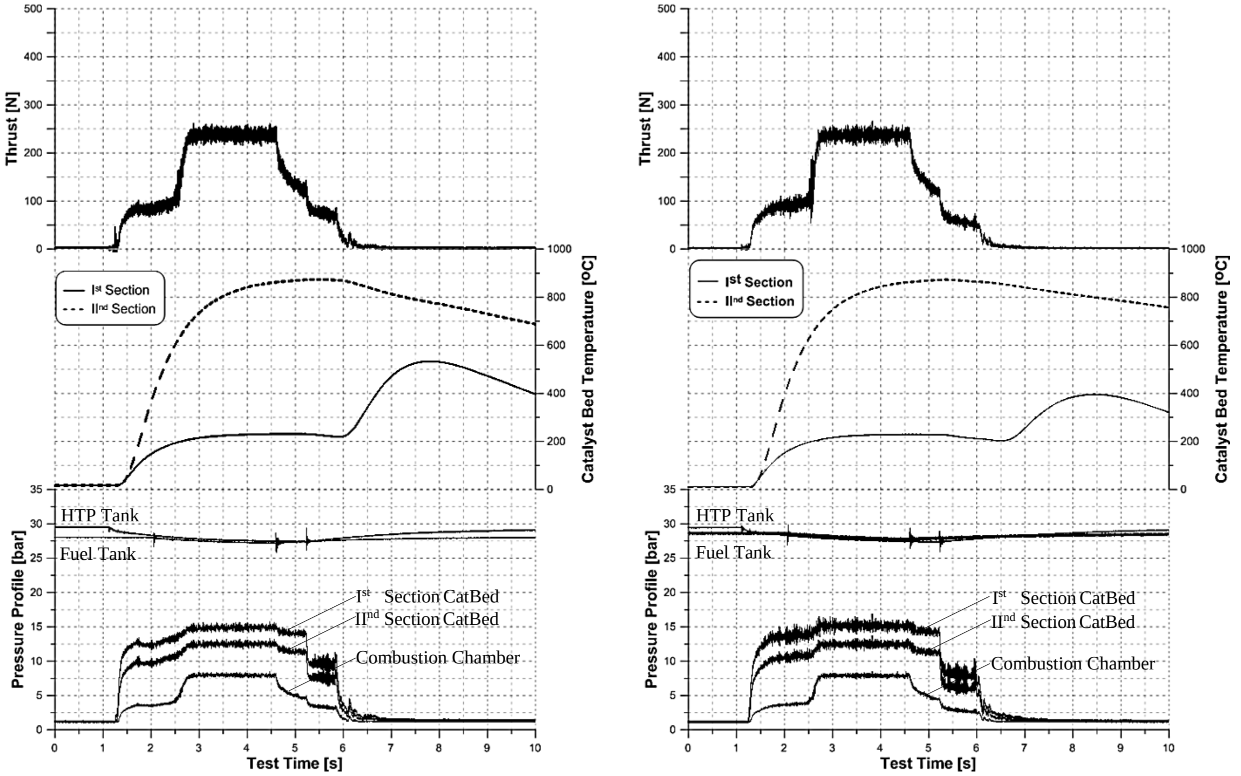

Figure 8. Measured parameters during the test of the kerosene ignition (8 injectors configuration).

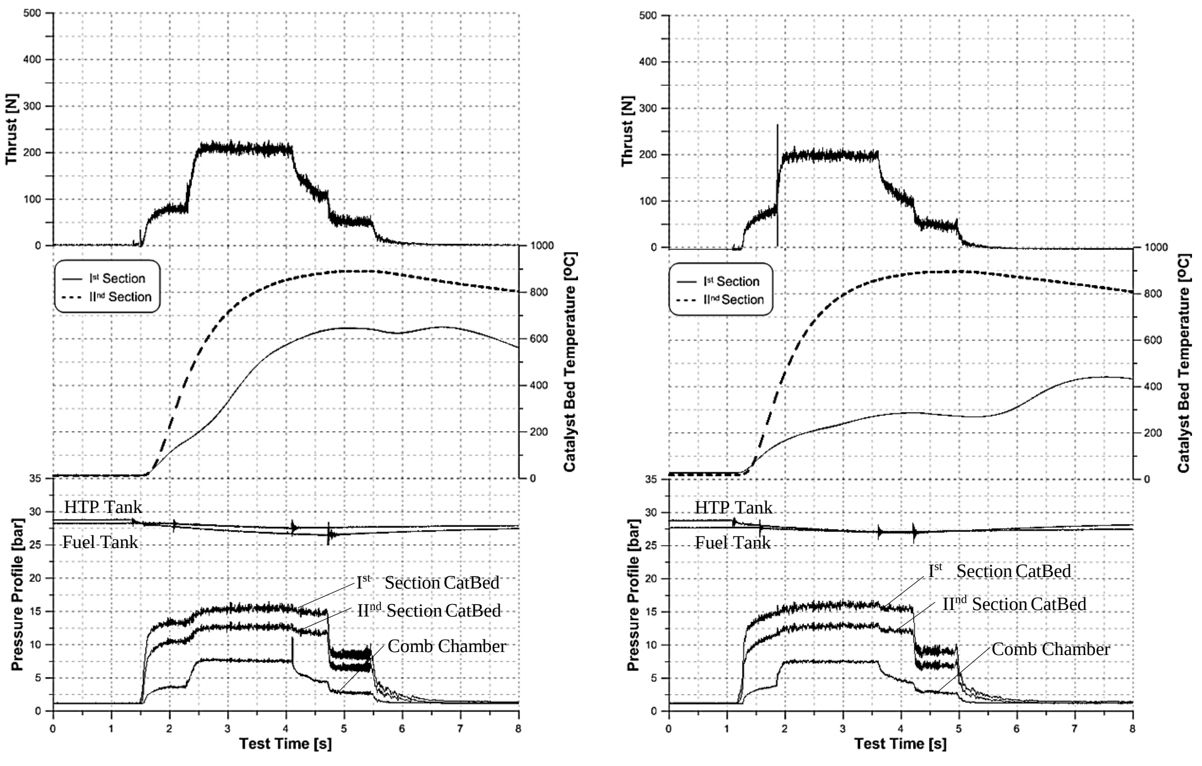

Figure 9. Measured parameters during the test of the kerosene ignition (4 injectors configuration).

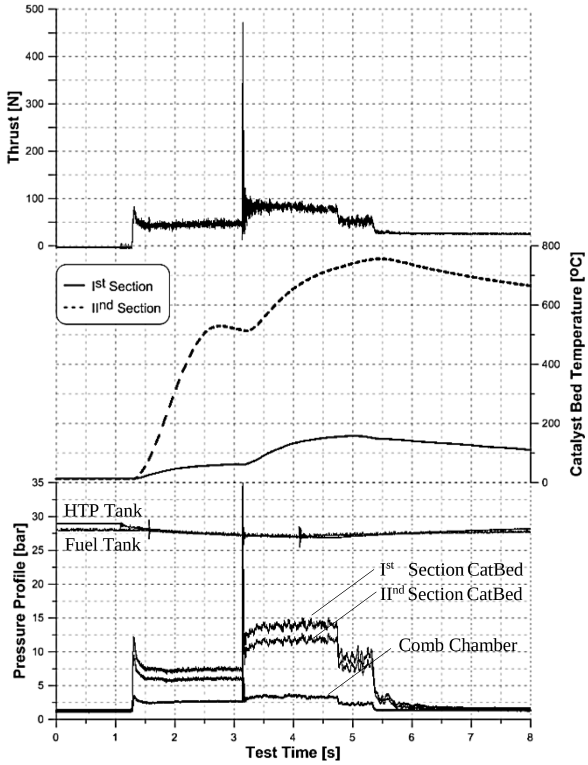

Figure 10. Measured parameters during the test of the isooctane ignition (8 injectors configuration).

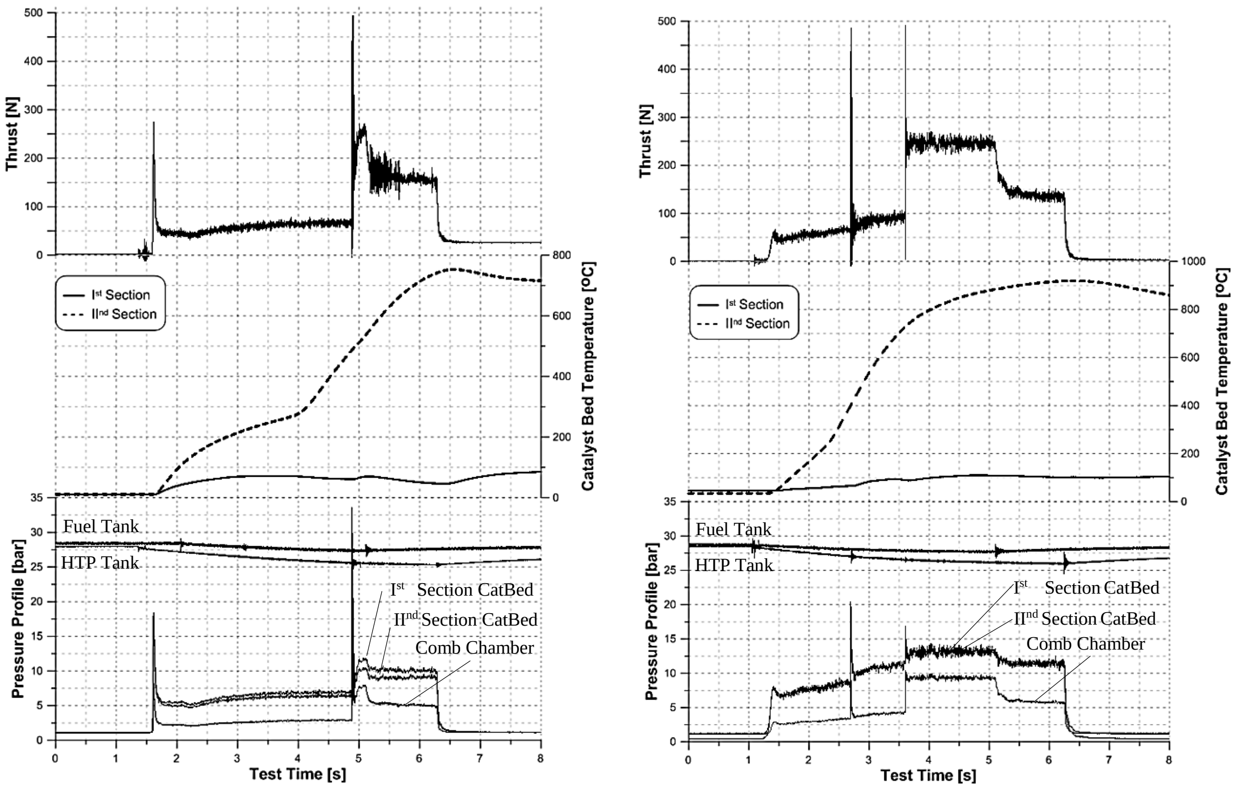

Figure 11. Measured parameters during the test of the isopropyl alcohol ignition (4 injectors configuration).

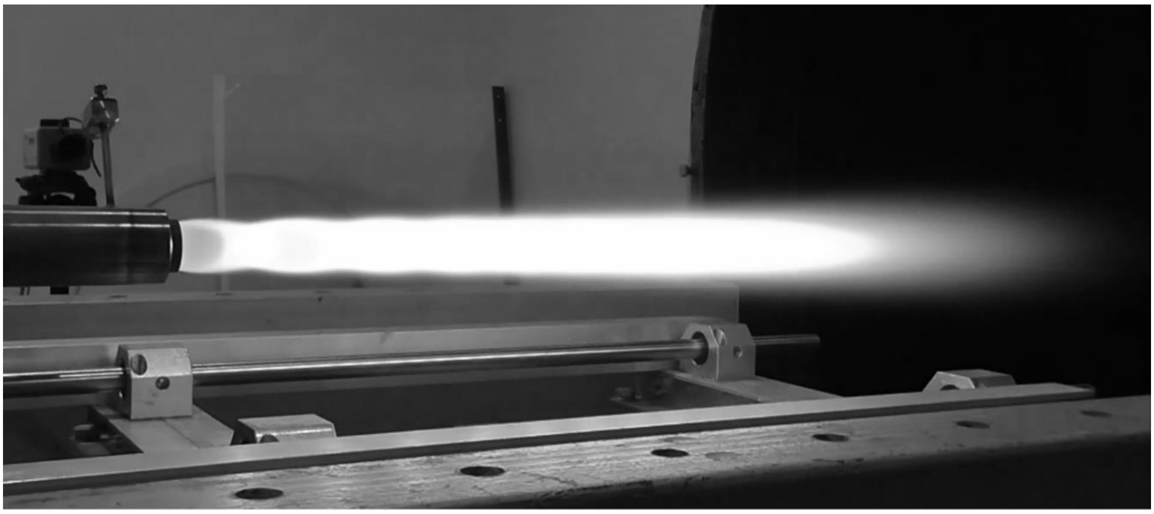

Figure 12. Engine during test

7. Conclusions and future plans

All conducted tests showed very promising results for further development. The obtained so far results will be used for subsequent optimization of the studied engine. A modular construction of the engine allows to investigate the influence of different parameters on its performance. A quasi – hypergolic ignition with decomposed 98%+ HTP was observed for each of fuel candidates. However, some cases may be characterized as so called hard start of the engine. This may be due not only the higher auto ignition temperature of the particular fuel, and as a consequence greater ignition delay times, but also to inability to precisely control the time of introduction of propellants into the combustion chamber. This assumption is based on the fact that the main propellant valves are located at considerable distance from the engine inlets and thus substantial dead volume arises, which impedes precise control of the engine start. This phenomenon will be thoroughly investigated in the near future, as it is vital issue for the study of ignition delay times that are planned as the next step of the engine development.
The performed work is a kind of milestone in the process of building a green propellant rocket engine that, in the future, may successfully replace the present constructions.

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