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Development of a Small Green Bipropellant Rocket Engine Using Hydrogen Peroxide as Oxidizer

Adam Okninski[1], Bartosz Bartkowiak[2], Kamil Sobczak[3], Dominik Kublik[4], Paweł Surmacz[5], Grzegorz Rarata[6], Blazej Marciniak[7]
Center of Space Technologies, Institute of Aviation, Warsaw, 02-256, Poland

Piotr Wolanski[8]
Institute of Heat Engineering, Warsaw University of Technology, Warsaw, 00-665, Poland

This paper gives an overview of the development of an environmental-friendly small bipropellant rocket engine at the Institute of Aviation in Warsaw, Poland. 98% concentration hydrogen peroxide oxidizer and Jet-A fuel are used. A reliable pressure-fed system was chosen and system assembly tests are on-going. The final goal is to enable building and flight-qualifying a larger engine, possible to be used as a large satellite thruster and orbit transfer propulsion system. The paper covers the design and tests of a sub-scale, high contraction ratio, 250-Newton-thrust rocket engine. Fuel is injected into the oxidizer gaseous catalytic decomposition products and pseudo-hypergolic ignition occurs. Results of test firings are presented, with thrust, pressure and temperature measurements given. Special attention is drawn to the process of kerosene autoignition. A novel investigation of kerosene autoignition for very low O/F values, when a high contraction ratio is utilized, was made.

Nomenclature

CR	=	combustion chamber Contraction Ratio
GEO	=	Geostationary Orbit
GRASP	=	Green Advanced Space Propulsion
HC	=	hydrocarbon
HP	=	Hydrogen Peroxide
HTP	=	High Test Peroxide
IoA	=	Institute of Aviation
KAIST	=	Korea Advanced Institute of Science and Technology
LRE	=	Liquid Rocket Engine
MMH	=	Monomethylhydrazine
NTO	=	Dinitrogen Tetroxide
O/F	=	oxidizer-to-fuel ratio
p_c	=	chamber pressure
p_e	=	nozzle exit pressure
RCS	=	Reaction Control System
SOTA	=	State-of-the-Art
TCA	=	Thrust Chamber Assembly
UDMH	=	Unsymmetrical Dimethylhydrazine

[1] Specialist in Rocket Propulsion, Space Technologies Department, adam.okninski@ilot.edu.pl, AIAA Member
[2] Engineer in Rocket Propulsion, Space Technologies Department, b.bartkowiak@ilot.edu.pl
[3] Associate Professor, Space Technologies Department, s.sobczak@ilot.edu.pl
[4] Associate Professor, Space Technologies Department, d.kublik@ilot.edu.pl
[5] Associate Professor, Space Technologies Department, p.surmacz@ilot.edu.pl
[6] Head of Propulsion Laboratory, Space Technologies Department, g.rarata@ilot.edu.pl
[7] Designer, Space Technologies Department, b.marciniak@ilot.edu.pl
[8] Professor, Aircraft Propulsion Department, wolanski@itc.pw.edu.pl

I. Introduction

THE need for efficient ecologically-friendly geostationary satellite propulsion can be seen in recent years. Platforms reaching GEO have masses in the range of 2 to 7 metric tons, what makes them the heaviest objects sent into space apart from space station modules, human exploration mission vehicles and large interplanetary probes. The necessary velocity increase varies depending on the transfer required. Some launch vehicles' upper stages enable reaching GTO and the satellite platform propulsion has to enable accelerations of about 1.5 km/s, whereas for transfers from LEO to GEO, with lower thrust levels, even 5 km/s may be needed[1]. This causes that the propulsion system configuration must allow meeting strict performance requirements, including operation of RCS thrusters. Usually chemical propulsion systems are chosen, due to the fact that they have been extensively used for decades. For most orbit transfer applications, storable bipropellant propulsion systems are utilized. NTO as oxidizer and hydrazine derivatives as fuel are commonly used.

II. State-of-the-Art satellite thrusters

A survey of existing chemical bipropellant and monopropellant rocket engines using hydrazine and its derivatives has been made by Okninski[2]. These propulsion systems are widely used in orbit and remain SOTA storable chemical propulsion systems.

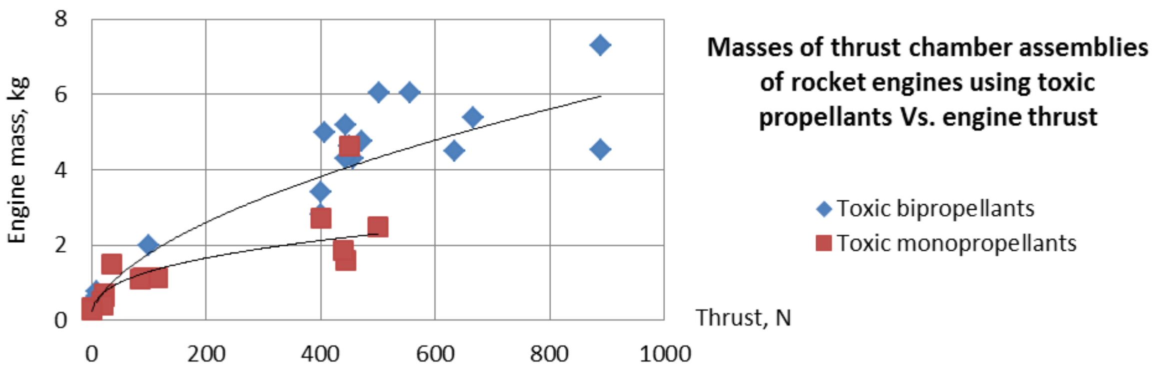

Figure 1. SOTA toxic rocket propellant engines' TCA masses

During the 2007' study concerning advanced chemical propulsion system development, conducted by NASA ad Aerojet, a goal of obtaining in-orbit performance of toxic rocket engines at levels of 3250 m/s was set[3]. This is near to the theoretical limit for N_2O_4-Hydrazine propulsion systems operating in pressure-fed mode. An analysis of Isp advancement of toxic small (between 400 and 600 Newtons of thrust) bipropellant systems during the last 50 years is plotted. It can be seen that over years a steady rise of performance was observed and the planned performance of rocket engines has been practically achieved nowadays. This was possible mostly due to the fact that material advances have been made. Hardly any increase in chamber pressure has been introduced by companies developing storable propulsion systems in recent years. The thrust to TCA weight ratio (T/W) of rocket engines between 400 and 600 N of thrust, despite technology advancements, does not increase. This is due to the fact that more focus is held on Isp gains since TCA mass is usually at least two orders of magnitude lower than the propellant total mass.

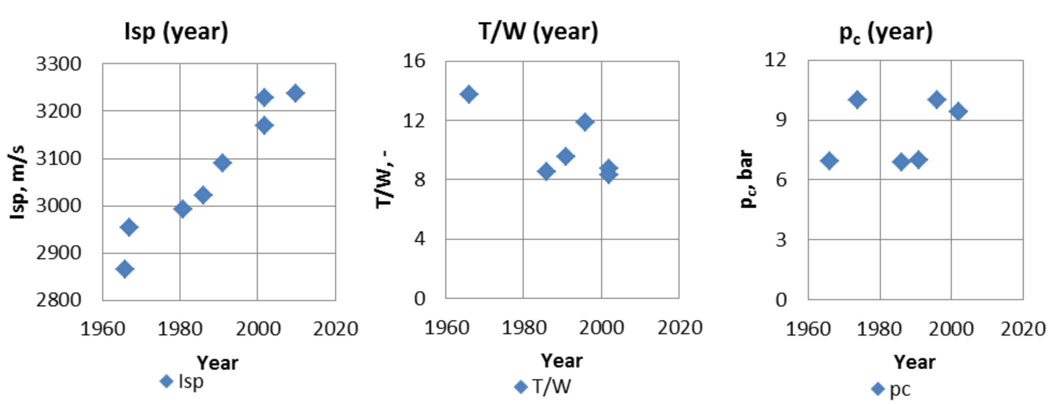

Figure 2. Trends in toxic bipropellant rocket engines of low thrust

These (traditional) propellants give reasonably high performance. However, their toxicity is becoming a serious concern in recent years. This is due to the rising costs of ground operations and labour during their production, handling and storage. The total impulses of GEO satellite main propulsion systems vary from 1 MNs do 10 MNs. Specific impulses achieved have reached above 95% of their theoretical performance and further advances in the field of storable toxic LRE can be done only by utilizing new materials, higher pressures and engine cycles. Therefore, more attention should be given to other storable propellant compositions. New-generation „green" oxidizers have been developed in recent years[4]. Their use in the form of monopropellant mixtures is being introduced. However, most of these oxidizers are still under development and their wide application as bipropellant rocket engine oxidizers may still be a matter of a few decades. Therefore, various researchers consider using highly concentrated hydrogen peroxide (HP) of HTP class with ecologically-friendly fuels in bipropellant rocket engines. Its performance in terms of Isp and density Isp was plotted using CEA software[5] and is presented in Fig. 2. Toxic propellants performance is also given for comparison.

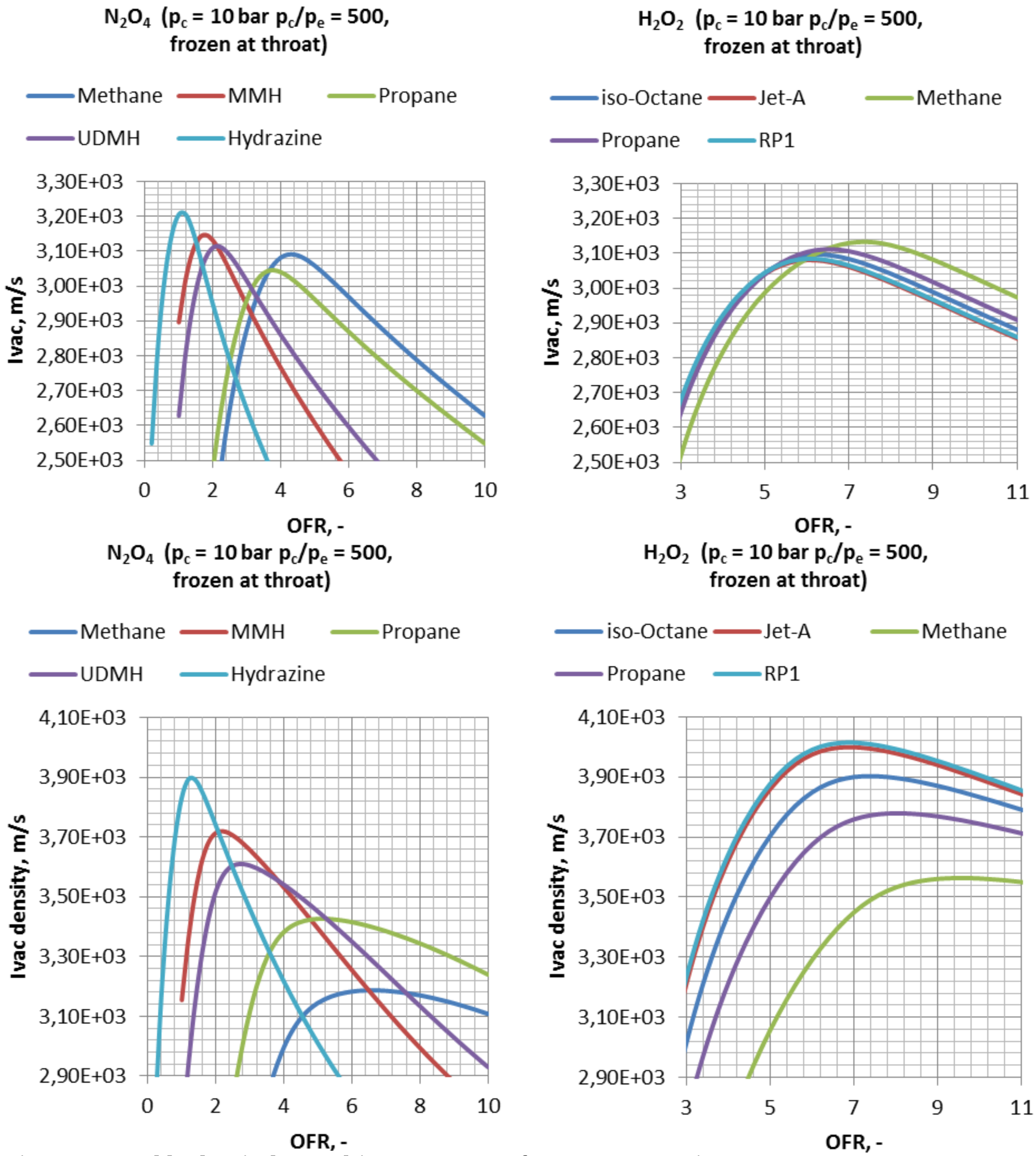

Figure 3. Storable chemical propulsion systems' performance comparison

III. Hydrogen peroxide as rocket oxidizer

Hydrogen peroxide is a well-known substance that may act as a monopropellant, as well as a bipropellant oxidizer. Due to the use of HP of HTP class in monopropellant RCS for nearly 60 years, its production for aerospace purposes is well established. However its quality (stability) can be significantly improved using new technologies and materials. Importantly, various bipropellant rocket engine configurations using HP as oxidizer have been investigated since World War 2[6,7,8]. Apart from early German research, most commonly, combinations of HP and kerosene were utilized. American and British research concerned designs for both military and space purposes. British research led to the development of large LRE, capable of powering the Black Arrow satellite launcher. Large bipropellant rocket engines using HP as oxidizer, such as the RD-161P, were also tested by Russians[9]. The RD-502 pump-fed engine used toxic pentaborane as fuel and allowed achieving a vacuum specific impulse of 380 seconds[10]. About 20 years ago, a "rediscovery" of HP for rocket propulsion applications occurred. Apart from national programs, various private companies, such as American Beal Aerospace and General Kinetics, started working on their own designs. However, their work has been unexpectedly abandoned. Development of HP/HC rocket engines in various scientific institutions was continued and an increased number of projects dedicated to HP rocket applications was launched in the last decade. With the GEO satellite market growing larger each year - official orders for 18 commercial GEO satellites were placed in 2012 and 23 in 2013 – particular interest in HP-based propulsion for orbital transfers can be seen[11]. Due to the use of higher concentration HP and its improved storability characteristics, density, as well as performance, various propulsion systems for in-orbit use are being investigated worldwide. Most notable research is being conducted at University of Purdue by Anderson et al, where combustion chamber sizing efforts and hypergolicity tests have been performed[12,13,14]. For nearly a decade, developments of green spacecraft propulsion systems are ongoing at KAIST, in South Korea[15,16,17]. The European GRASP project enabled the demonstration of efficient use of HP with ethanol. In Russia, at Moscow Institute of Aviation a small family of bipropellant thrusters, using kerosene as fuel and 94-98% HP as oxidizer, was developed[18]. The idea of global sustainable development and, therefore, use of environmentally-friendly propellants for satellite and spacecraft applications, caused an increased interest in HP/HC rocket engines in numerous other countries, such as: China, Italy, Japan, Malaysia, Poland and Taiwan[2]. Advances in the field of highly-efficient and reliable catalysts and hypergolic systems show a promising future for green storable propulsion systems. Moreover, the knowledge of combustion processes has had rapidly developed since the 70' due to new tools such as advanced CFD methods and more precise test equipment. Despite having slightly lower Isp, bipropellant rocket engines using HP as oxidizer exhibit a high density-performance alternative for SOTA toxic systems. All in all, a "new-old" green propulsion pathway may be observed.

IV. State-of-the-Art kerosene autoignition research

Decomposition efficiency, chamber pressure, O/F and CR are used, when kerosene autoignition, in decomposed HP, transients are analyzed. Kerosene ignition requires higher decomposition flow temperature for low chamber pressures, what was shown by Sadov[19]. Sadov investigated fuel injection for chamber pressures between 10 and 18 bar. His results fit the autoigniiton chain reaction theory well. However, a slightly lower range of pressures has the key importance during bipropellant rocket engine start-up, when chamber pressures for in-orbit applications are utilized. It was been demonstrated by Sisco et al, that for low equivalence ratios, kerosene autoignition in decomposed HP is not a problem, however, some difficulties may occur for very low O/F ratios[13]. Jo et al. demonstrated autoignition for mixtures with equivalence ratios between 0.26 and 1.61, but did not conduct experimentation for higher values[17]. Sisco et al. also showed that for lower chamber CR, ignition does not occur easily[13]. However, for application of quazi-hipergolic ignition of kerosene, the influence of all o of the design parameters mentioned, should be analyzed. This includes the possibility of achieving autoignition for high equivalence ratios. Although O/F values below four occur mostly locally in the combustion chamber, they may be present during kerosene autoignition transients. When the fuel is injected shortly after oxidizer flow initiation, the catalyst bed is not preheated and its performance is lower than optimal. Therefore, there is a larger kerosene ignition lag and low O/F values can occur before ignition. For relatively low chamber pressures and high equivalence ratios, autoignition is problematic and its delays are significant. However, this may be mitigated by using a high contraction ratio and this problem has been dealt with in this paper. The only production-introduced, HP/HC rocket engine with a CR of above 10 was the pump-fed LR-40[13].

V. Project overview

In Poland, the Institute of Aviation Space Technology Department rocket propulsion team is developing propulsion systems using HP since 2007, focusing on hybrid and monopropellant rocket engines[20]. With its own, patented, HP concentration technology (allowing to obtain 99.9%+ HTP grade), first bipropellant actives started in late 2013. The interior project of the IoA has the goal to present the feasibility of developing a low-cost, reliable, pressure-fed GEO satellite thruster using HP and HC[2]. The technology demonstrator designed and tested was to have a minimum thrust of 250 Newton, when used at sea level with a nozzle expanding combustion products to ambient pressure. This corresponds to a vacuum thrust in the order of 400 Newton for an expansion ratio of 300 and chamber pressure of 10 bar, what is well in the range of propulsion systems used for orbital transfers. The ultimate version of the HP/HC engine is to enable reaching specific impulses in the range of existing bipropellant engines, being an attractive alternative for toxic systems.

VI. Engine design

The engine configuration chosen uses a catalyst bed enabling the decomposition of 98% HP into gaseous H_2O and O_2 and achieving a quasi-hypergolic ignition after injecting HC fuel into the ≈ 900°C decomposition products flow. An simplified overview of phenomena occurring in the TCA can be seen in Fig. 4.

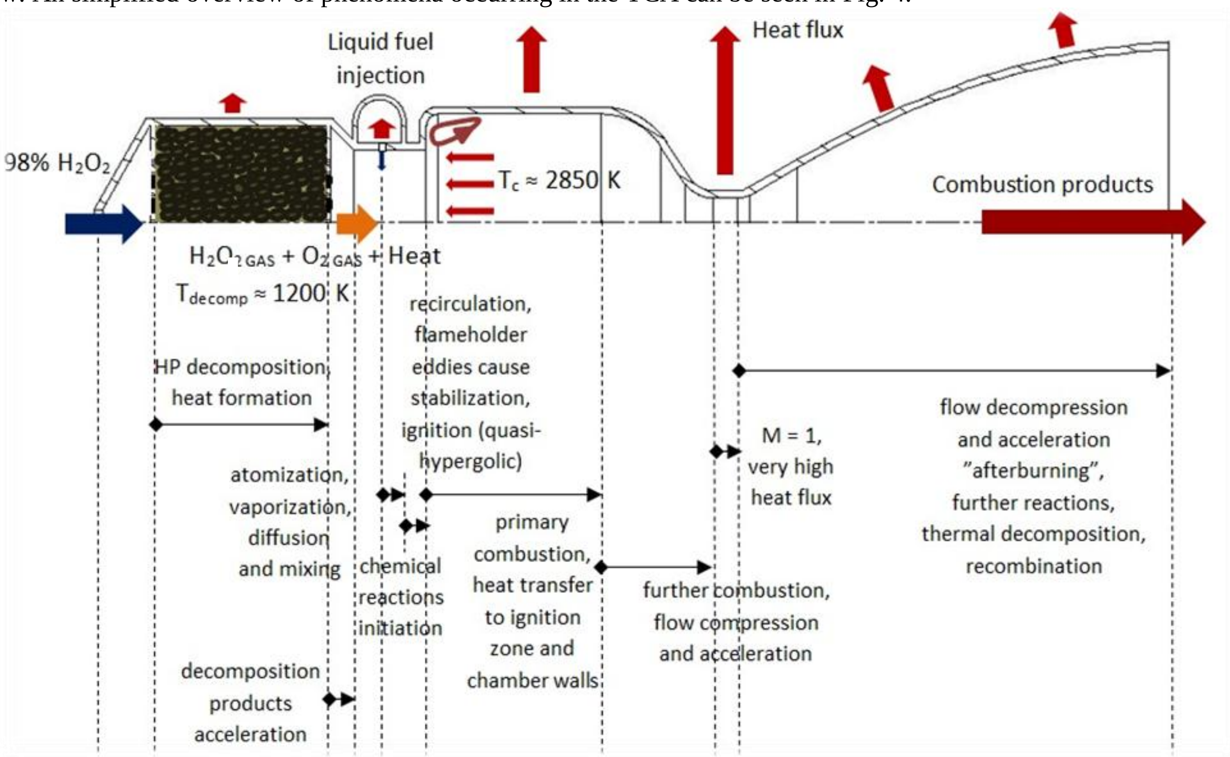

Figure 4. Possible TCA configuration for HP/HC propellants

Test engine parameter	Value
Chamber inner diameter	50 mm
Chamber contraction ratio	10.5 [ ]
Chamber pressures to be tested	9-16 bar
Oxidizer-to-fuel ratios to be tested	3-10 [ ]
Nozzle expansion ratio	10 [ ]

Table 1. Test engine's design parameter values

The rocket engine design was based on experience obtained during the development of HP hybrid rocket engines[21] and utilized some of their elements including the catalyst bed. The chamber used during first tests had a much to high length[22], however this element was decided to be optimized after several firings on basis of obtained data for different chamber elongations. Engine performance for different organic fuels was obtained using NASA CEA 2 software by Gordon and McBride[5]. However, for initial firings, Jet-A was utilized due to its wide use in similar projects worldwide. During first design iterations, SOTA liquid rocket engine methodologies, accessible in literature, were used[23,24,25]. Further work consisted of flowfield modeling using commercial CFD codes. Heat fluxes and thermal issues were addressed by Bartkowiak[26], Okninski[27] and Matyszewski. Both steady-state and unsteady heat transfer was analyzed. Finally, an ablative thermal protection was used. Having The initially proposed geometry remained practically unchanged, however, the development of a second version of the thruster, dedicated for laboratory testing and optimization, had been simultaneously started. The initial TCA configuration is presented in Fig. 5.

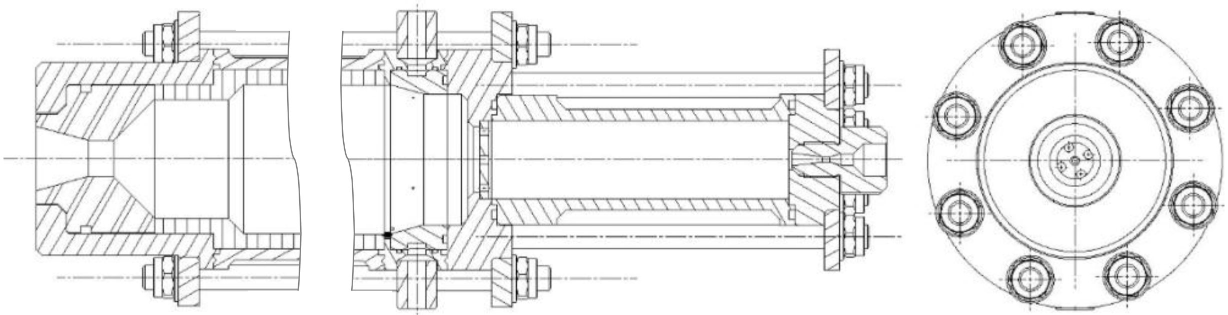

Figure 5. First, preceding optimization, TCA design[22]

VII. Tests' results

Up to date, numerous catalyst bed tests, as well as first bipropellant mode firings, were done using the smallest test stand located at the IoA Propulsion Laboratory. A constant feeding pressure up to 24 bar was utilized, with Nitrogen used as the pressuring agent. Flow release was done using standard solenoid valves. In this paper catalyst bed tests are described coarsely and two bipropellant firings are presented. Both of the latter were conducted for relatively low O/F values.

A. Kerosene autoignition tests

This experimentation consisted of kerosene injection into decomposed HP flow. Fuel valve opening was executed 0.2-0.5 seconds after oxidizer flow initiation. Both nozzleless and full TCA were tested. During preliminary firings at IoA, chamber pressures between 2 and 10 bar were investigated, what is complementary to Sadov's research[19]. In all tests, for catalyst bed described in this paper, autoignition occurred.

B. Catalyst bed tests

Catalyst bed tests were conducted during the bipropellant project. Measurements of catalyst chamber outlet pressure and flow temperature were made. All of the heterogeneous catalyst configurations utilized aluminum oxide (Al_2O_3) catalyst support with manganese oxides and additional compounds, including samarium and lanthanum, as the active phase[28]. These were developed by Rarata and Surmacz and used primarily in the IoA hybrid rocket motor project. An overview of results obtained during firings which lasted above one second can be seen in Fig. 6. Importantly, the wide range of performance is due to the fact that various catalyst bed configurations were tested. Also, different feeding pressures were investigated. For some, the cavitation venturi did not limit the mass flow rate of HP. Moreover, some modifications of the catalyst bed length were done. All in all, despite non-uniform test conditions, it can be seen that for pressures that will be used in bipropellant HP/HC rocket systems, HP decomposition efficiencies, are fully satisfactory if the best-performance catalyst beds are utilized. Jet-A autoignition temperature is around 485 K, however, for elevated pressures and an oxygen rich atmosphere, this value significantly decreases.

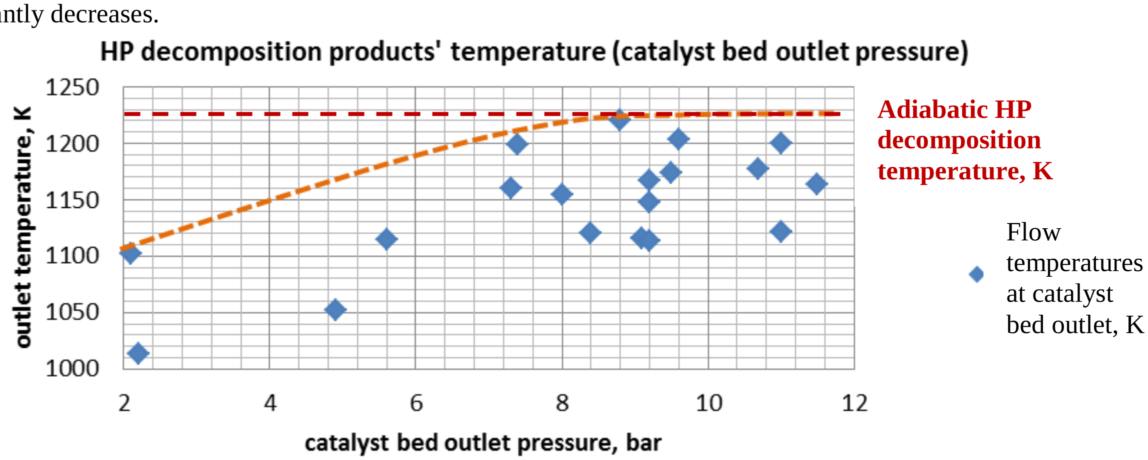

Figure 6. Example results of catalyst bed tests performed

Catalyst bed loadings in the order of 100 kg/m/s^2 were used. Notably, higher performance catalyst beds are being already tested by Rarata and Surmacz during the "Research of the composite catalyst bed for decomposition of highly concentrated hydrogen peroxide to be applied in monopropellant thruster" project under the ESA program, enabling their comprehensive characterization[28].

C. Bipropellant rocket engine tests

1. Test B98.Jet-A.015

The first hot bipropellant firing using a full TCA was performed for a low O/F value of 3.4. For safety reasons, fuel injection was done 0.5 seconds after monopropellant mode start. Ignition of kerosene occurred 120 ms later (defined as a pressure relative rise of over 5%). However, the thrust level reached half of the nominal thrust value after further 120 ms. High thrust bipropellant mode occurred 0.7 seconds after oxidizer flow initiation. A relatively smooth transition to full bipropellant mode was observed. Thruster performance, calculated on basis of collected firing data, was compared to CEA Isp output assuming a frozen flow of combustion products from nozzle throat.

Test engine parameter	Value
O/F	3.4
Mean chamber pressure (bipropellant mode)	11 bar
Isp_{real}	1840 m/s
Isp_{theory}	1947.8 m/s
Isp_{real} / Isp_{theory}	94.5%

Table 2. Test B98.Jet-A.015 summary

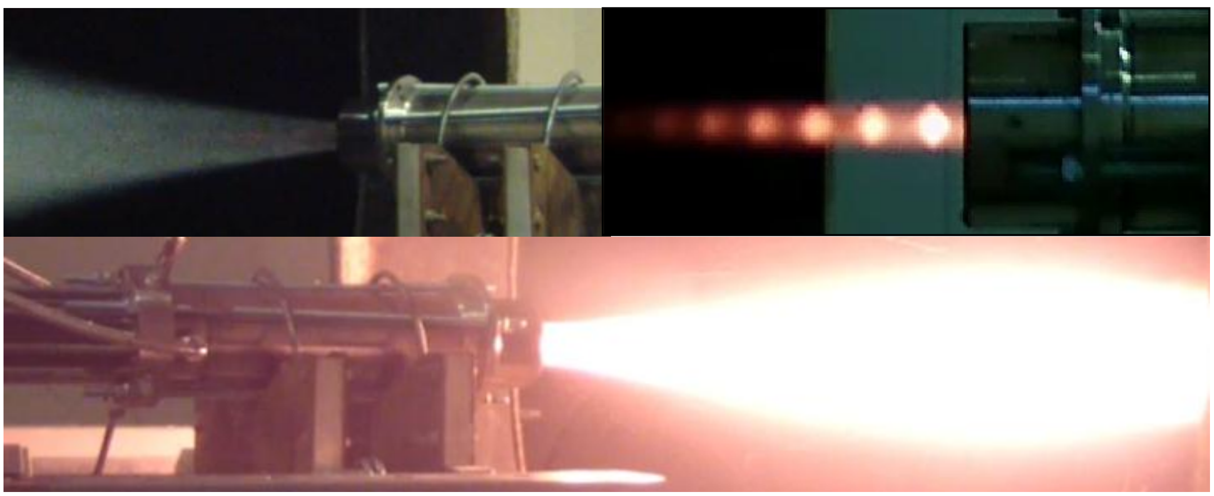

Figure 7. Test B98.Jet-A.015 captions presenting the moment of fuel ignition, steady bipropellant performance and end of engine firing

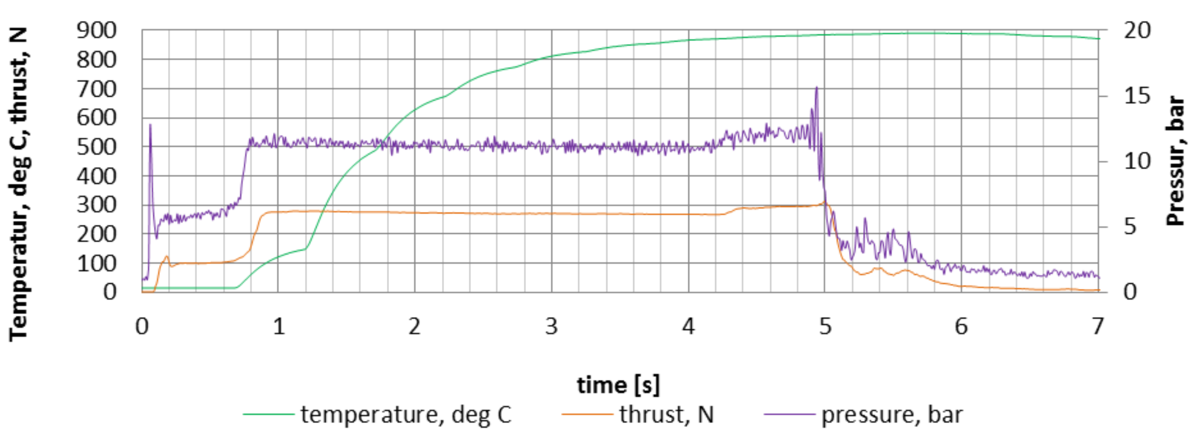

Figure 8. Test B98.Jet-A.015 data – catalyst bed outflow temperature, thrust and presure plots

2. Test B98.Jet-A.019

This firing is another example of test conducted for low O/F values. An average O/F value of 3.4 was used and the mean chamber pressure during bipropellant mode operation was 15 bar. Fuel injection was done 0.2 seconds after monopropellant mode start. Jet-A ignition took place after 131 ms and half of the nominal thrust level was reached after a further interval of 59 ms. What is notable, before reaching nominal thrust, high-amplitude pressure oscillations with an approximate frequency of 50 Hz were measured. They can be seen in Fig. 10. Due to worse combustion characteristics, a notably lower level of Isp efficiency was obtained.

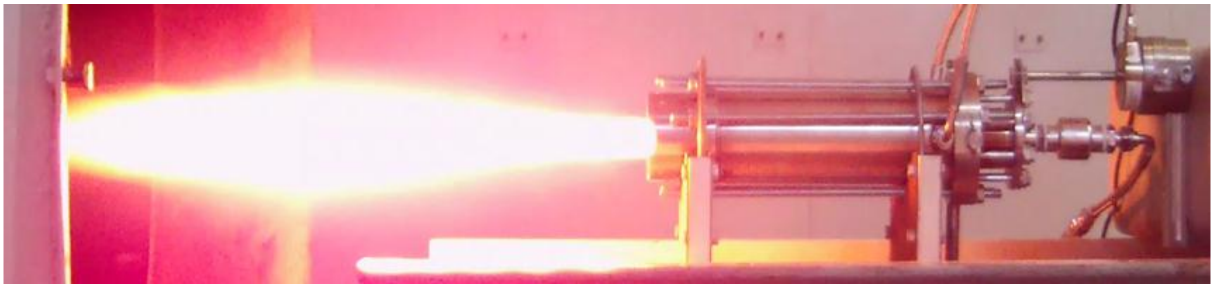

Figure 9. Test B98.Jet-A.019 bipropellant mode

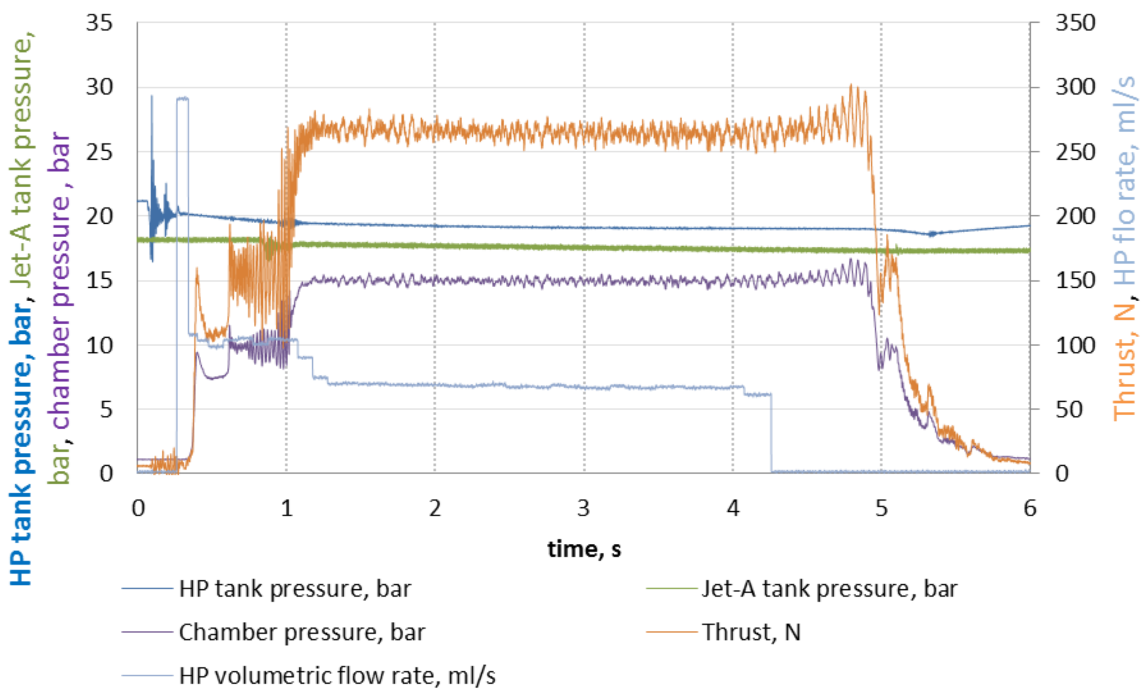

Figure 10. Test B98.Jet-A.019 data

VIII. Conclusion

The described project allowed the development of a simple bipropellant rocket engine giving a specific impulse efficiency over 94% what is a very good result for a small propulsion system, even if this result can be slightly too optimistic, due to the measurement system utilized. Jet-A is being used with 98% hydrogen peroxide of HTP class, showing acceptable, at this moment of development, ignition lags (delay times). A higher O/F ratio, close to 7, will be used for high engine performance. However, up to date combustion efficiency was not the main issue of the development process. This version of the engine will still be under development in order to find the possible engine performance envelope for different O/F ratios, feeding pressures and catalyst bed configurations. Later, work on chamber sizing should be also done. The few firings completed up to date, show that more advanced bipropellant rocket engines can be built. However, several phenomena occurring during initial fuel injection can lead to temporary instabilities. Necessary optimization of a propulsion system for GEO transfer satellite propulsion system is on-going and the development of a second thruster dedicated to laboratory testing is being done. Future research will consist of the development of a 400-500 Newton satellite thruster technology demonstrator.

A few conclusions can be drawn from this paper:

1) Kerosene ignition characteristics in decomposed HP flow from past studies were confirmed.
2) Results obtained showed Jet-A autoignition in the 2-10 bar chamber pressure range, what is complementary to Sadov's results[19]. However, more test have to be done in order to define the low-pressure-temperature autoignition boundary.
3) It can be seen that for large CR values, despite very low O/F ratios tested, autoignition is feasible
4) Despite still not optimized catalyst beds, ignition delays of about 100 ms were achieved. When higher pressures and oxidizer-rich mixtures are utilized, these values may be substantially decreased. For test B98.Jet-A.019, the fuel flow was initiated after 0.2 seconds, what caused the fact that the catalyst bed was still not operating in its high-performance (good decomposition) mode. When longer monopropellant firing preludes fuel injection, further ignition delay minimization can be achieved.
5) For a shorter fuel injection delay after oxidizer flow initiation, large combustion instabilities occurred. The discovered transition phenomena have to be studied in detail during further experimentation. When instabilities occurred, a performance decrease was noticed. However, more stable performance, after reaching bipropellant mode, was demonstrated.
6) Possible superiority of HP/HC combinations in comparison with toxic SOTA bipropellants can be seen for some applications. Even for unoptimized rocket engines, high Isp and HP decomposition efficiencies were achieved, what shows that HP/HC thrusters are relatively predictable and high performance propulsion systems may be developed.

Acknowledgments

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