Green Propellants Research at Alta S.p.A.

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A summary of the activities carried out in the last four years by Alta S.p.A. on hydrogen peroxide for propulsive applications is given. In the framework of European Space Agency and Italian Government funded projects, a significant know-how on this matter has been gained by Alta in collaboration with the Universities of Messina and Pisa. Tests have been carried out in the GPRT facility, an easily reconfigurable and expandable experimental apparatus for the characterization of the propulsive performance of small monopropellant thrusters. After an intensive phase of development and characterization, several advanced catalytic beds capable of effectively decomposing hydrogen peroxide have been obtained. In order to characterize the catalysts under real working conditions two reconfigurable monopropellant thruster prototypes were simultaneously designed and successfully tested at Alta. Endurance tests on the LR-III-106 and CZ-11-600 catalysts allowed for accumulating respectively 2500 s and 2000 s of continuous thruster operation decomposing about 13 kg of high grade hydrogen peroxide.

Nomenclature

c^*	=	characteristic velocity
D	=	catalytic bed diameter
F	=	thrust
G	=	bed load or mass flux ($G = m/A$)
I_{sp}	=	specific impulse
L	=	catalytic bed length
m	=	propellant mass flow rate
T_c	=	combustion chamber temperature
η_{c^*}	=	characteristic velocity efficiency
$\eta_{\Delta T}$	=	temperature efficiency
τ	=	residence time
Φ	=	mass mixture ratio (Oxidizer/Fuel)

I. Introduction

THE research on green propellants for space rocket technology is continuously in progress in view of achieving a sufficient confidence level for their application in commercial propulsion systems. Aiming to the main objective of substituting toxic propellants as hydrazines and nitrogen tetroxide, a large number of technological solutions has been investigated by several research teams to optimize the critical components of propulsion subsystems operating with green propellants. As a green propellant, high concentration hydrogen peroxide (HTP) has recently received a

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renewed interest and the critical issues linked with its use have been reconsidered. In order to take advantage of the H_2O_2 decomposition reaction in rocket propulsion applications, the development of an effective, reliable and durable catalytic bed is required. It should provide fast and reproducible performance, be insensitive to poisoning by stabilizers and impurities contained in the propellant, as well as capable to sustain the large number of thermal cycles imposed by typical mission profiles in small satellite applications. The catalyst can suffer considerable degradation as a consequence of the severe operational conditions experienced during H_2O_2 decomposition. The stabilizers typically present in the hydrogen peroxide solutions are chemical compounds containing phosphate or stannate which, during catalytic bed operation, could progressively bind to the active phase and consequently lead to its deactivation. In addition, the catalytic metal could undergo chemical and textural changes because of the high temperatures and the strong oxidizing atmosphere, leading to crystallization and particle size growth. All the above mentioned phenomena contribute to decrease the catalyst surface activity, consequently reducing the lifetime of the thruster. In the last four years, Alta S.p.A. has been involved in several projects related to the development of hydrogen peroxide monopropellant thrusters with advanced catalytic beds. This activities were funded by European Space Agency, in the framework of the LET-SME program for small and medium enterprises, and by the Italian Ministry for Production Activities under its funding program D.M. 593. In this paper, an overview of the main results obtained by Alta in the framework of the above projects is given. More in detail, Section II is devoted to the presentation of Alta's Green Propellant Rocket Test Facility (GPRTF), an easily reconfigurable experimental apparatus especially designed for performance characterization of small monopropellant (H_2O_2) and bipropellant (H_2O_2-hydrocarbon) thrusters. Some of the thruster prototypes designed and tested by Alta are described in the following Section III. Being the catalyst the key element of a HTP monopropellant thruster, Section IV summarizes the activities that were performed to finalize the development of efficient catalytic bed solutions. Finally, the main goals achieved during thruster prototypes testing are presented in Section V.

II. Green Propellant Rocket Test Facility (GPRTF)

Alta's Green Propellant Rocket Test Facility (GPRTF) is an easily reconfigurable and expandable experimental apparatus especially designed for performance characterization of small monopropellant (H_2O_2) and bipropellant (H_2O_2-hydrocarbon) rocket engine prototypes and catalytic reactors operating at thrust levels in the 1-10 N and 25-100 N ranges[1,2]. Figure 1 shows a picture of the GPRTF. The facility includes a propellant feed system and a thrust balance. The hydrogen peroxide lines and the main tank are made of AISI 316 stainless steel, internally coated with Teflon. Hydrogen peroxide is stored in a 2.5 liters tank and pressurized by means of Nitrogen. Its physical conditions are continuously monitored by means of a J-type thermocouple and a gauge pressure transducer. If the peroxide starts to decompose, the tank can be vented to the atmosphere by a remotely controlled valve or, in the absence of the operator, by the combination of a relief valve and a burst disc calibrated for opening at a given pressure. The propellant mass flow rate is controlled by means of interchangeable cavitating venturis and monitored by a Coriolis flowmeter. The venturi working conditions are continuously monitored by a differential and a downstream pressure transducer.

The thruster is mounted on a one degree-of-freedom dynamometric force balance. A number of transducers have been installed for evaluating the performance of the thruster prototype and the catalytic reactor. In particular, the conditions of the thrust chamber downstream of the catalytic bed are monitored by means of a K-type thermocouple placed on the chamber axis and by an absolute pressure transducer, which has been mounted recessed for protection from the high temperatures developing during chamber operation. A subminiature compression load cell, mounted on the balance cradle, measures the engine thrust. The catalytic bed performance is monitored by measuring the absolute pressure after the injector and the differential pressure between the supply line to the injector and the thrust chamber. Finally, five K-type thermocouples can be mounted along the bed for monitoring the local catalyst temperature. Figure 1 reports the locations of all the transducers and thermocouples installed in the GPRTF and used for the experimental activities.

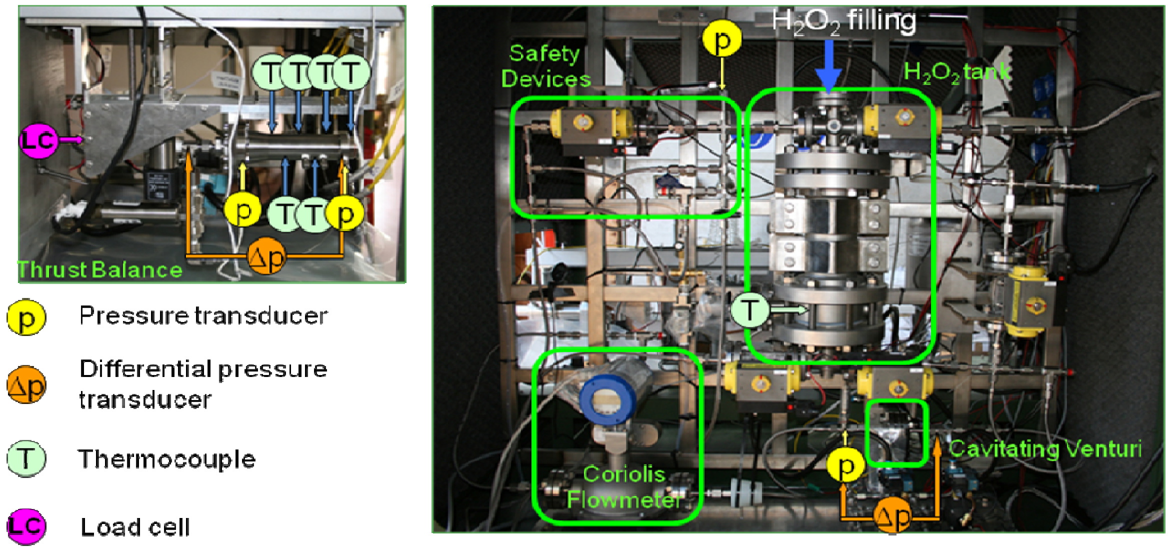

Figure 1. Picture of the Alta's Green Propellant Rocket Test Facility showing the thrust balance (left) and the hydrogen peroxide feeding line (right) together with the transducers arrangement and location.

A DC source, capable of supplying different output voltages, provides the transducers with the required electric excitations. The data coming from the sensors and transducers installed in the facility are acquired and transferred to a personal computer by means of a National Instruments acquisition board, capable of acquiring 32 analog and 48 digital channels at a maximum sampling rate of 1.25 MS/sec. The acquisition board is connected to different SCXI conditioning and filtering modules, also produced by National Instruments. A LabVIEW® data acquisition and control program is used for real time display of the data and for recording all the acquired signals. A 20 Samples/s acquisition rate has been actually used in most of the experimental activities. Pressure, mass flow rate and thrust signals have been low-pass filtered by means of a 10 Hz cut-off frequency.

In a second phase the test facility (Figure 2) has been upgraded in the framework of an ESA-funded project aiming at the main objective of experimentally characterize a 50 N thruster prototype operating with gaseous ethane as fuel and hydrogen peroxide as oxidizer.

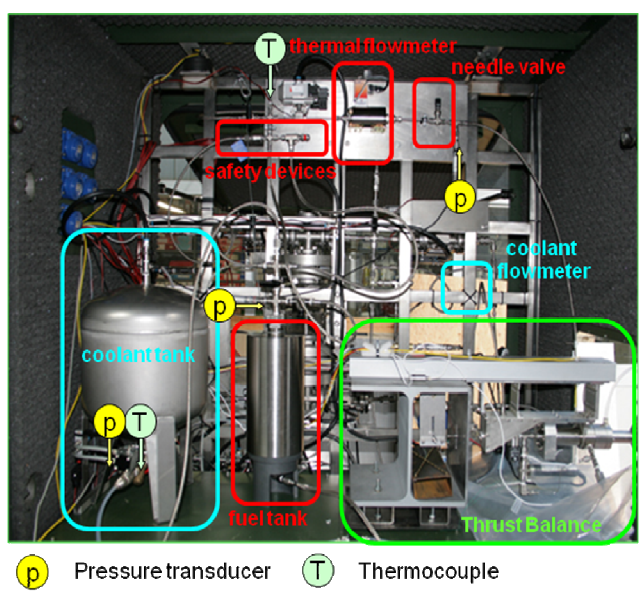

Figure 2. Picture of the Alta's Green Propellant Rocket Test Facility showing the fuel and coolant supply lines together with the transducers arrangement and location.

Gaseous ethane has a vapor pressure at ambient temperature close to 44 bar. Thanks to a dual tank configuration, this fuel property has been utilized to simultaneously pressurize both hydrogen peroxide and ethane. Besides the dual tank set up, the facility has been provided with a new feeding line for ethane with a micrometric valve and a flow-meter necessary for controlling and measuring the mass flow. This configuration enables a highly simplified propulsion system by eliminating the problems associated to the cost, weight and complexity of additional pressurized propellant storage vessels. During a typical firing the following measurements are recorded:

1. hydrogen peroxide tank delivery pressure;
2. hydrogen peroxide tank temperature;
3. cavitating Venturi differential pressure;
4. cavitating Venturi outlet pressure;
5. hydrogen peroxide mass flow rate;
6. ethane tank delivery pressure;
7. ethane temperature before the flowmeter;
8. ethane mass inside the tank;
9. ethane mass flow rate;
10. ethane injection pressure;
11. coolant tank temperature;
12. coolant pressure;
13. coolant mass flow rate;
14. exhaust coolant temperature;
15. differential pressure across the catalytic bed;
16. absolute pressure after the catalytic bed;
17. temperature of the hydrogen peroxide decomposition products;
18. five temperatures along the catalytic bed;
19. pre-heating temperature of the catalytic bed;
20. thrust.

III. Thruster Prototypes

During the activities on green propellants carried out by Alta S.p.A., two monopropellant and one bipropellant thruster prototypes have been designed and their propulsive performance experimentally investigated. The first prototype has been designed for investigating different bed configurations under a wide range of operating conditions. The catalytic bed has been realized by means of a modular cartridge for rapid reconfiguration and simplified filling with the catalyst pellets (see Figure 3). The cartridge consists in a 36 mm I.D. AISI 316L stainless steel casing, long enough to accommodate a 100 mm long catalyst bed between the upstream spring-loaded injection plate and the downstream distribution plate. Two AISI 304 stainless steel screens (37x37 mesh size and 0.2 mm wire diameter) are interposed between the plates and the catalyst for retaining the pellets. Cylindrical inserts with different lengths (L = 30, 60, 90 mm) and inner diameter (D = 18 and 25 mm) can be inserted inside the cartridge before filling it with the catalyst pellets, allowing for easy and independent control of both the dwell time τ and the bed load G. The injection and distribution plates have a 50% open area ratio, realized by means of two different series of holes. The chamber pressure can easily be adjusted by replacing the separate convergent-divergent nozzle, flanged on the external housing and sealed by a MICATHERM S15 face gasket. The thruster prototype has been designed for 5 g/s of 87.5% HP mass flow rate. Using standard isentropic 1D gas dynamic relations three different conical nozzles have been designed for realizing adapted expansions from 10, 15 and 20 bar (chamber pressure, p_c) to one atmosphere (ambient pressure, p_a).

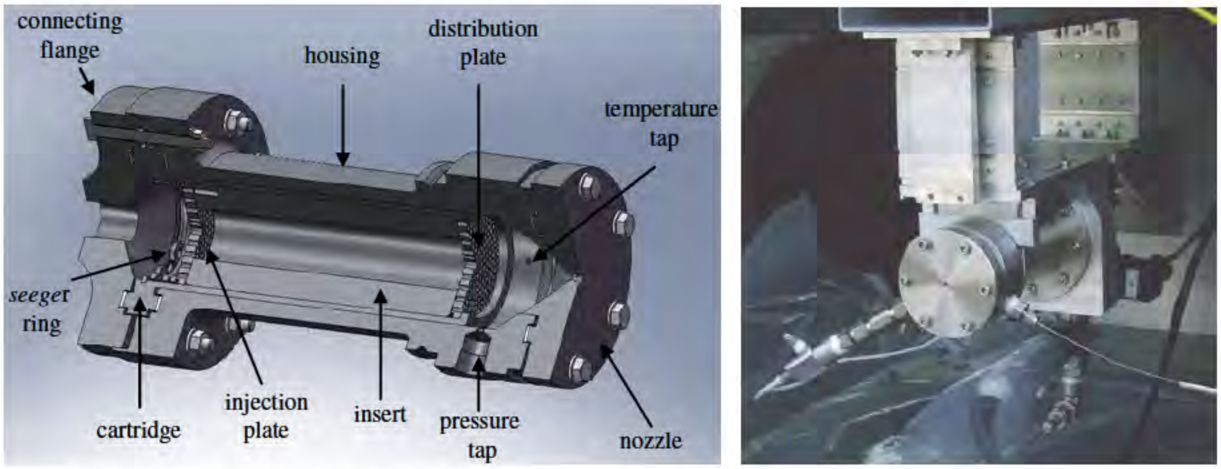

Figure 3. Cut-off assembly drawing of the thruster prototype (left) and a picture of the thruster before a firing test (right).

Based on the experience gained by the preliminary tests performed with the prototype reported in Figure 3 (see section V.A), a new reconfigurable monopropellant thruster prototype has been successively designed according to the following guidelines:

- reducing the empty volumes and the wall thickness of the engine elements with respect to the previous prototype, in order to decrease as much as possible the start-up transient and the wall heat losses;
- guaranteeing the possibility of adjusting the length of the bed and its propellant load *G* within reasonably wide ranges, in order to adapt them to the observed performance of the catalyst;
- simplifying the design and mounting of the bed housing and its related components;
- introducing several temperature probes along the bed in order to better detect and monitor the possible degradation of the catalytic activity;
- supplying the H_2O_2 to the catalytic bed by means of a suitable spray injector, in order to reduce the wetted portion of the bed, as well as the thrust build-up transient.

Figure 4 shows a cut-off assembly (left) and a picture (right) of the second thruster prototype. The thruster has been designed to operate with 5 g/s of 90% H_2O_2 at a nominal chamber pressure of 15 bar and 10 kg/(m^{2}s) of bed load, developing a nominal thrust of 6.5 N. Similar to the former thruster prototype, three conical nozzles (separate elements) have been designed in order to allow atmospheric operation of the thruster without nozzle flow separation at three values of mass flow rate (5, 17 and 28 g/s) and the same chamber pressure (15 bar). The main element of the thruster is the cylindrical casing, interfaced at the fore end to the flanged connection to the thrust balance and at the aft end to the threaded nozzle. MICATHERM S15 has been used again between the flange and the L shaped support, while a copper face gasket has been used for the nozzle. Differently from the former prototype, the catalytic reactor has been provided with five temperature taps realized by means of 1/16 NPT connectors welded on the outer wall of the thruster casing. The maximum available volume for the catalytic bed in the channel between the injection and distribution plates is 30 cm^3, with a maximum length of 60 mm. The design of the distribution plate has remained unchanged, while the injection plate was an AISI304 cap-shaped grid with a 40 mesh index kindly provided by EUROSAF S.R.L. Finally, the nozzle nominally operates at a pressure drop of 5 bar, generating droplets with 110 μm volumetric mean diameter and a jet angle of 58°. No modifications to the GPRTF thrust balance have been carried out for the experimental campaign on the second prototype.

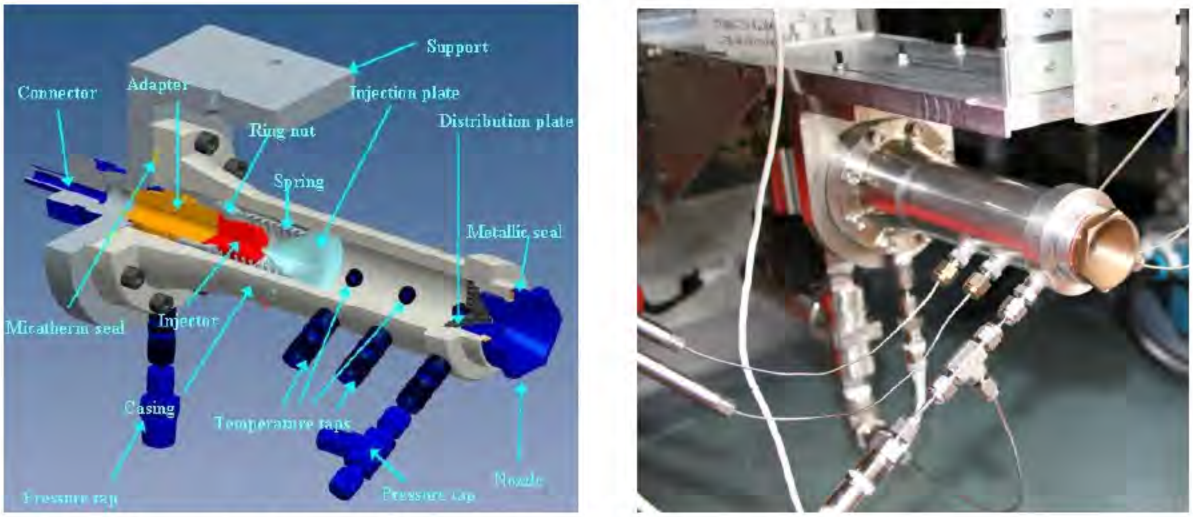

Figure 4. Cut-off assembly drawing of the second thruster prototype (left) and a picture of the thruster before a firing test (right).

Thanks to the experience gained during the experimentation of monopropellant thruster prototypes, it has also been possible to undertake the design of a bipropellant prototype operating with hydrogen peroxide and gaseous ethane. Looking at the CAD drawing in Figure 5, it is clear that in this configuration the first monopropellant prototype has been used as gas generator for the bipropellant rocket engine. After the H_2O_2 decomposition products leave the catalytic bed, they are directed toward the injection manifold where ethane is azimuthally inserted by means of 12 injectors. The two propellants can therefore be mixed before they enter the combustion chamber. Considering an expected combustion temperature close to 2600 K, a regenerative cooling system has been especially designed. To remove the heat released during thruster operation, coolant (water) has been pressurized up to 10 bar for a mass flow of 75 g/s. The rocket engine prototype has been designed to generate a thrust of 50 N with a H_2O_2 mass flow of 15 g/s and a mixture ratio (Φ) of 9.1. Similarly to the other prototypes, the bipropellant engine has been tested in the GPRT facility. In Figure 6 a picture of the prototype before a firing test is reported.

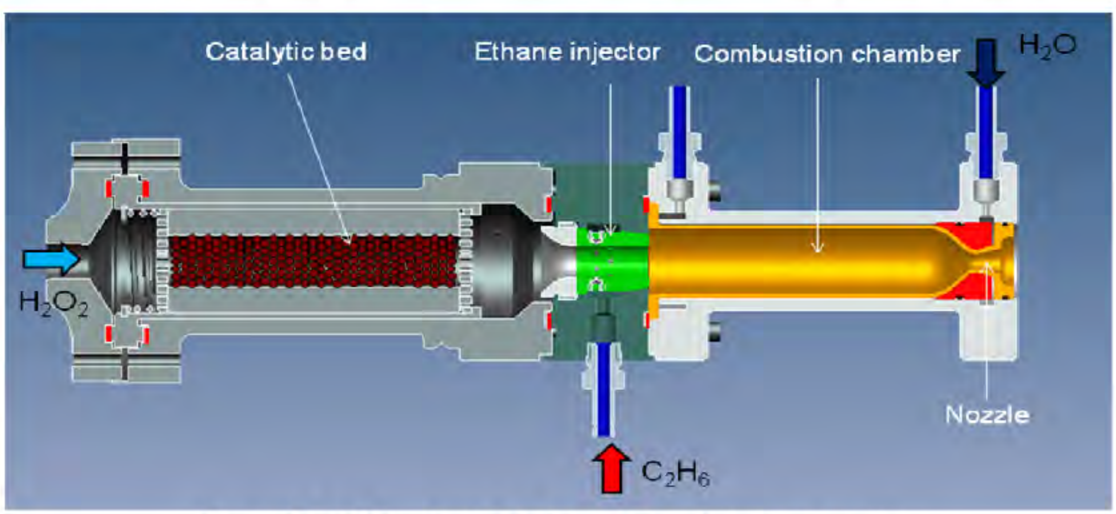

Figure 5. CAD drawing of the bipropellant thruster prototype.

Concerning the advancement status of the H_2O_2-C_2H_6 bipropellant thruster prototype, the Fuel Vapor Pressurization (FVP) concept has been successfully demonstrated under all the foreseen working conditions. Further investigations are needed to accomplish the auto-ignition of the mixture.

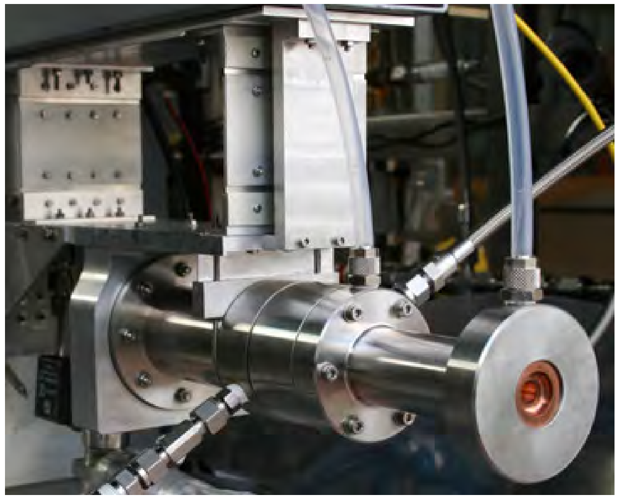

Figure 6. Picture of the bipropellant prototype mounted on the thrust balance.

IV. Catalyst Development Status

The recent (2006 to 2009) development of catalysts for hydrogen peroxide decomposition at Alta S.p.A. has been carried out in collaboration with the Department of Chemistry and Industrial Chemistry of Pisa University and the Department of Industrial Chemistry and Material Engineering of Messina University. Figure 7 shows the catalyst development and characterization work-flow. The initial stages of the activity have been focused on screening different metallic cations and oxides to identify which of them could have better catalyzed the H_2O_2 decomposition reaction. In this phase a constant pressure test reactor capable of indirectly evaluate the catalytic activity of the materials has also been designed and assembled. A picture of the experimental set-up is shown in

Figure **8**. As a first step, the activity of several powders (silver and manganese oxide) and silver metallic wires has been measured[3]. Subsequently, the most promising metallic cations have been selected by preparing different catalyst samples by means of novel impregnation techniques. A commercial carrier of gamma alumina (γ-Al_2O_3) in shape of spheres has been impregnated with suitable precursors to depose silver, ruthenium, platinum, palladium and manganese dioxide on its surface. Activity test results demonstrated that platinum is the most active metal to effectively and rapidly decompose hydrogen peroxide[4]. This finding represented the principal conclusion of the first phase and was then utilized to direct and organize the following steps of the activity. After having noticed the breakup of the gamma alumina substrate during the first thruster prototype tests because of the strong thermal stresses induced by the decomposition reaction, the research and development of carriers with high thermo-mechanical resistance has become the most critical point to be investigated. As a consequence, the principal objective of the two chemistry departments was the development of a carrier with a surface area which could simultaneously assure adequate thermo-mechanical resistance and wettability by precursor solutions. The University of Pisa developed two novel techniques for platinum deposition and prepared about 50 catalyst samples on a large selection of commercial substrates. Different materials have been used as substrates including carborundum (SiC), cordierite, vitreous reticulated carbon (VRC) as well as all different alumina phases (theta, delta and gamma). As a result three catalysts named LR-III-97, LR-III-106 and LR-IV-11 showed to be suitable for the thruster characterization[5,6].

Differently, the University of Messina has developed a catalyst based on alumina spheres coated with a thin film of $Ce_xZr_{1-x}O_2$, which is known to stabilize noble metal particles in oxidation reactions and simultaneously enhance the substrate resistance[7]. Ceria-Zirconia based catalysts have never been used for hydrogen peroxide decomposition yet although they were largely used in three way catalysts for automotive converters. About 15 catalyst samples of this typology have been prepared by iteratively changing the preparation in agreement to the results obtained by the activity tests. After this phase the CZ-11-600 catalyst has been selected as candidate to be tested in actual working conditions.

As a consequence, after the development phase, four resulting catalysts (LR-III-106, CZ-11-600 and LR-IV-11 LR-III-97) have been selected to carry out the endurance tests with the second thruster prototype.

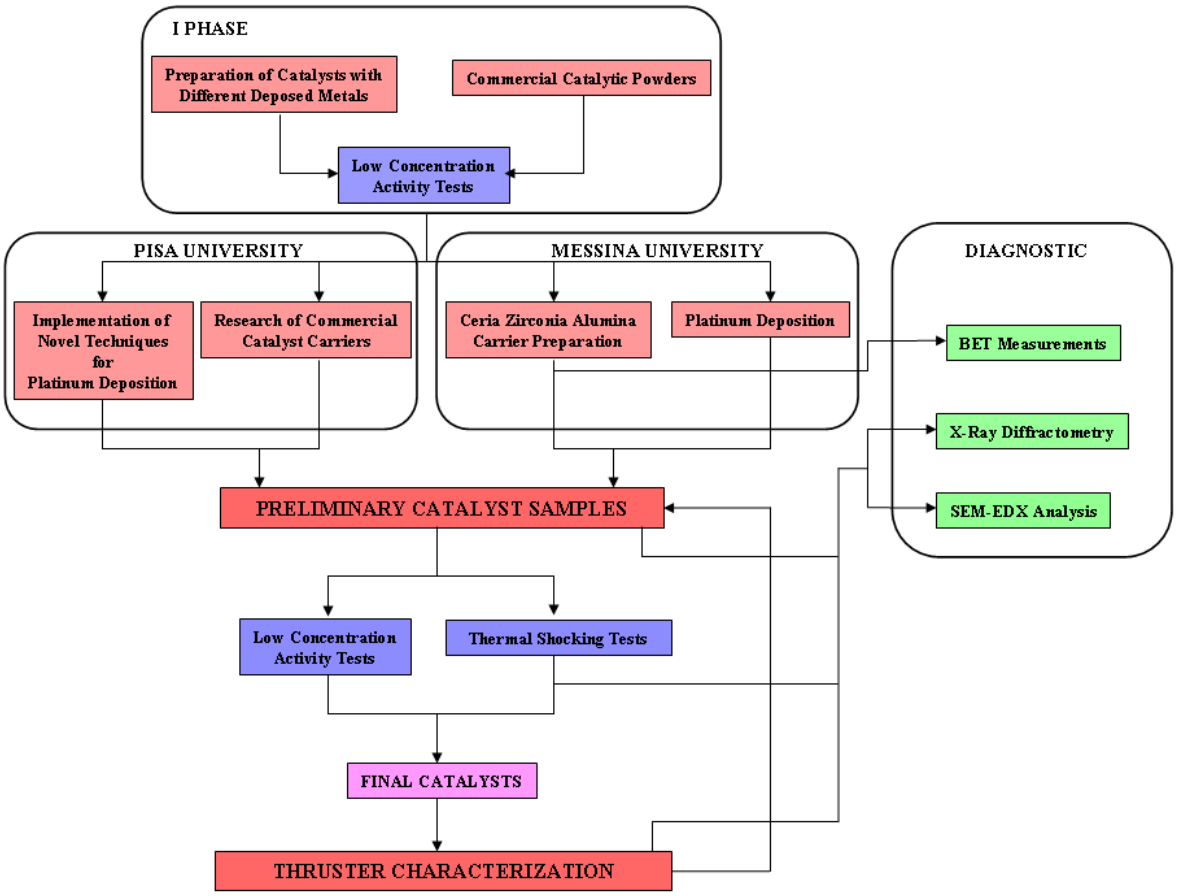

Figure 7. Catalyst development work-flow.

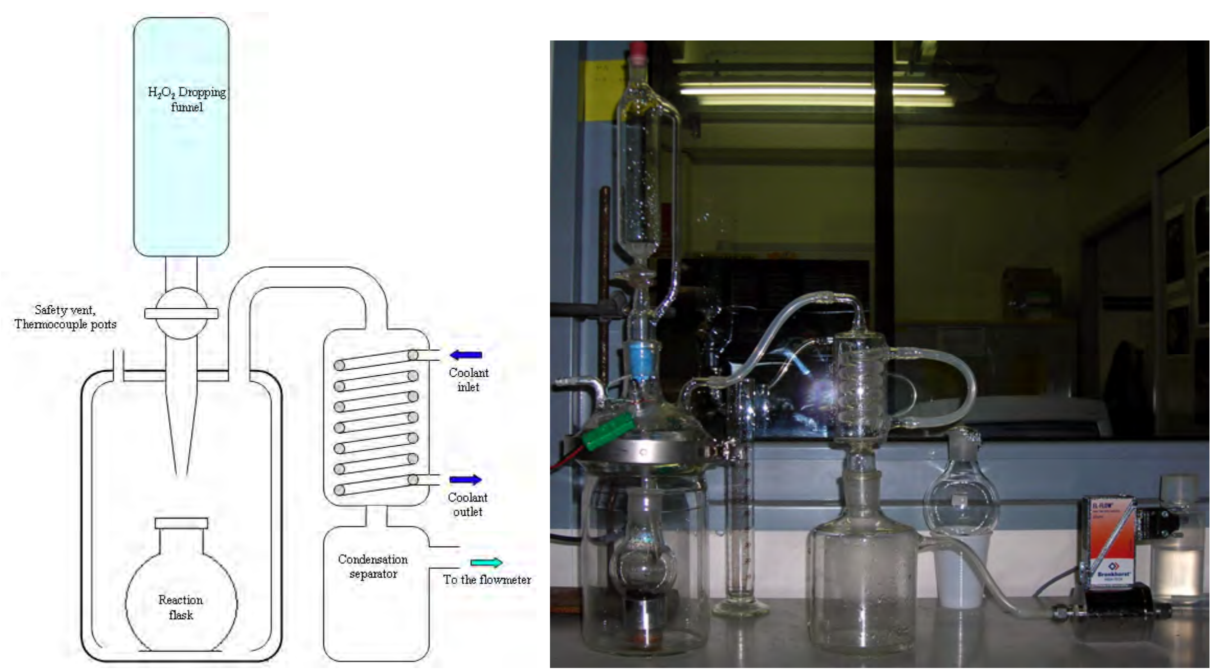

Figure 8. Scheme (left) and picture (right) of the test bench for the evaluation of the catalysts activity.

V. Experimental Campaigns

A. Preliminary Tests

In order to characterize and compare the propulsive performance of two catalytic beds, a series of tests have been performed using the first thruster prototype. Considering that catalyst preparations have been iteratively changed according to results of thruster characterization, the FC-LR-87 catalyst was the most performing one in view of this first phase of the experimentation. It is composed by an α–Al_2O_3 substrate with 4 m^2/g of surface area coated with metallic platinum. By means of an advanced coating technique it has been possible to achieve a value of 35 wt% for the metal superficial load despite the low value of surface area[5].

Another platinum catalyst (here indicated as HERAEUS), produced by a major commercial manufacturer and supported on alumina granules with monodispersed diameters ranging from 0.71 to 0.85 mm, has also been procured in order to compare the FC-LR-87 propulsive performance to that of a typical commercial benchmark for space propulsion applications. The HERAEUS catalyst employs the same substrate used for commercial catalysts produced for hydrazine decomposition. The catalyst carrier has been obtained by means of a suitable sol-gel procedure capable of yielding nearly spherical granules for more uniform bed packing and reduced pressure drop. Three different sets of experiments have been conducted in order to evaluate the propulsive performance of the catalytic beds under investigation. In Table 1, for each experiment, the main operational conditions and the obtained results are summarized. In the last column of the table, numerical values of the main performance indexes are reported: C-star (η_{c*}) and temperature ($\eta_{\Delta T}$) efficiencies, pressure drop across the catalytic bed and generated thrust. More details about the preliminary tests can be found in Romeo et al.[6].

Table 1. Results and working condition of the preliminary tests.

Test ID	Catalyst	Operational Conditions	Results
#1	***FC-LR-87***	150 s steady state firing. Bed load G=9.92 kg/(m^2s)	η_{c*}: 93% $\eta_{\Delta T}$: 93% *Pressure drop*: 0.3 bar *Thrust*: 5.3 N
#2	***FC-LR-87***	150 s steady state firing. Bed load G=19.26 kg/(m^2s)	η_{c*}: 94% $\eta_{\Delta T}$: 88% *Pressure drop*: 0.65 bar *Thrust*: 5.2 N
#3	***FC-LR-87***	Sequence of pulsed firings. First of 40 seconds followed by three pulses of 20 sec and three final pulses of 10 sec. Bed load G=19.26 kg/(m^2s)	η_{c*}: 82%-90% $\eta_{\Delta T}$: 80%-90% *Pressure drop*: 0.5 bar *Thrust*: 5 N
#4	***HERAEUS***	220 s steady state firing. Bed load G=19.26 kg/(m^2s)	η_{c*}: 90% $\eta_{\Delta T}$: 86% *Pressure drop*: 1 bar *Thrust*: 5.2 N

The preliminary experimental campaign confirmed the excellent flexibility of the prototype to easily change catalyst operating parameters but revealed long start up transients unsuitable for propulsion applications. For what concerns catalysts, the thermo-mechanical resistance of the α-Al_2O_3 substrate and the effectiveness of the preparation technique have been fully demonstrated. Additionally, the efficiencies achieved with FC-LR-87 catalyst were comparable to those of the commercial benchmark catalyst. In order to reduce the start-up transient and enhance the decomposition activity, the design of the second prototype was carried out according to the previously reported guidelines.

B. Endurance Tests

According to the results of the low concentration activity tests, the catalyst characterization activity and the preliminary tests, four catalysts resulted to be suitable for undergoing an endurance test with the second thruster prototype. In Table 2 the main properties of the chosen catalyst samples are reported.

Table 2 Main characteristics of the catalytic systems used in the thruster experimental campaign.

Identification code	Catalyst	Support	Nominal metal load (wt %)	SEM metal load (wt%)
LR-III-97	$Pt/\alpha\text{–}Al_2O_3$	*0.6/4*	2	35
LR-III-106	$Pt/\alpha\text{–}Al_2O_3$	*0.6/4*	1	3
LR-IV-11	$Pt/\theta\text{–}\alpha\text{–}Al_2O_3$	*0.6/75*	1	2.5
CZ-11-600	$Pt/Ce_{0.6}Zr_{0.4}O_2/Al_2O_3$	*0.6/75*	10	10

For effective comparison between the various types of catalysts, all the experiments have been conducted using the same concentration of hydrogen peroxide (90% ±0.8%) and the same injection nozzle at equal values of the bed load (G = 10 kg/(m^{2}s)) and length of the catalyst bed (L = 60 mm).

Table 3. Cumulative firing time for all tested catalysts.

Endurance Test ID	Catalyst	Cumulative Firing Time [s]
#1	*LR-III-97*	740
#2	*LR-III-106*	2500
#3	*LR-IV-11*	900
#4	*CZ-11-600*	2000

To summarize and compare the performance and lifetimes of the tested catalysts, it has been decided to plot in Figure 9, Figure 10 and Figure 11 their efficiencies and pressure drops as functions of the cumulative time from the beginning of the test. All the tested catalysts showed high decomposition and propulsive efficiencies (η_{c*}> 90%). In particular, the LR-III-106 and CZ-11-600 catalysts operated respectively at η_{c*} = 98% for almost 2500 s and at η_{c*} = 95% for almost 2000 s. It is worth comparing the performance of the LR-IV-11 and CZ-11-600 catalysts. Even though these catalysts have been realized on the same porous alumina carrier, in case of CZ-11-600 sample, the Ceria-Zirconia film interposed between the Platinum active species and the ceramic substrate has reduced the open porosity of the catalyst. Considering that for both catalysts the lifetimes have been mostly limited by the excessive increase of bed pressure drop, the use of Ce-Zr coating allowed for enhancing about 2.5 times the CZ-11-600 lifetime. As for LR-III-106 catalyst, its propulsive performance resulted to be the most promising one in terms of efficiencies, duration and pressure drop and confirmed the great potential of the novel deposition technique.

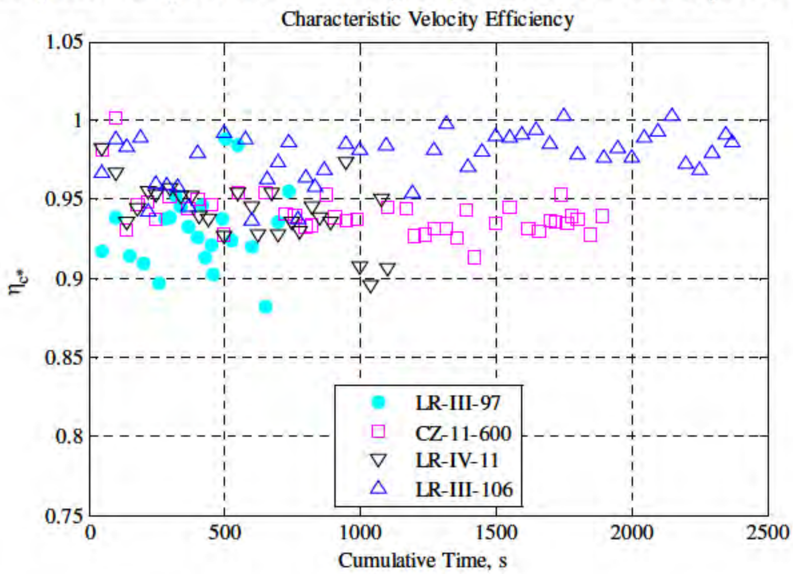

Figure 9. Comparison between the C-star efficiency of the catalysts.

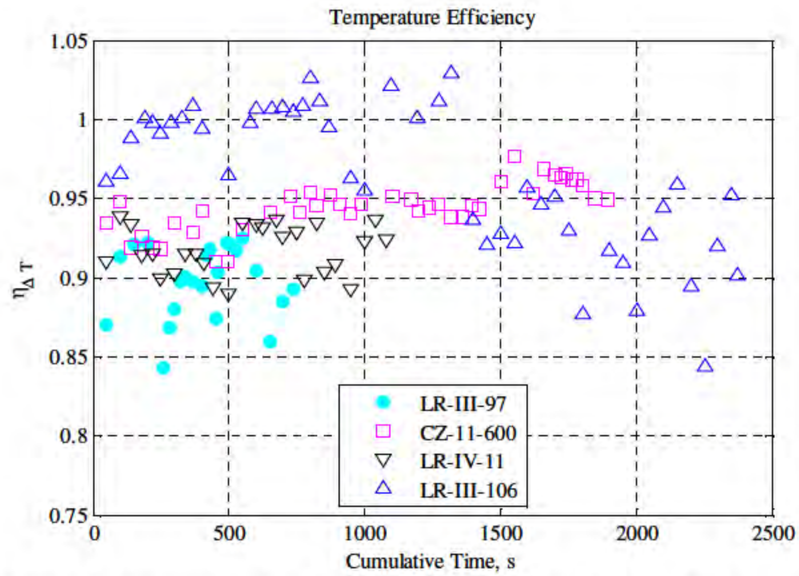

Figure 10. Comparison between the temperature efficiency of the catalysts.

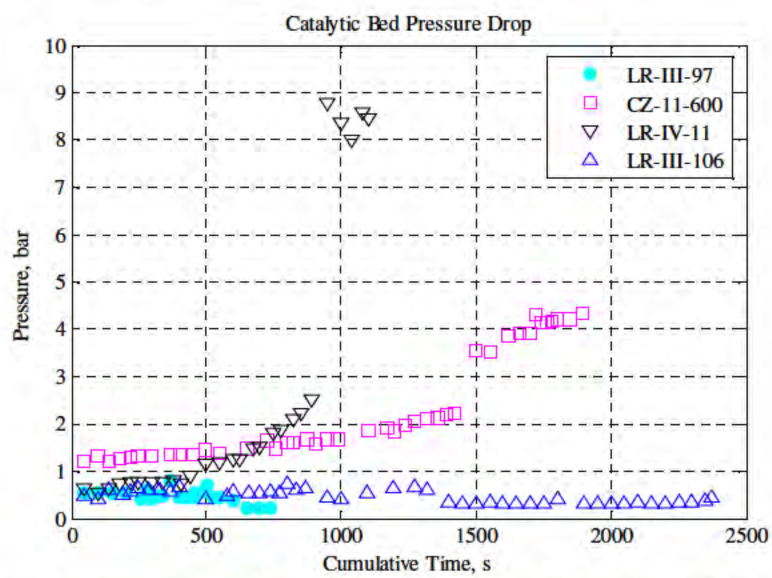

Figure 11. Comparison between the pressure drop inside the catalytic beds.

The mechanical atomization of the propellant, together with the reduction of the empty volumes in the thruster, have allowed for a significant reduction of the start-up transients with respect to the former thruster configuration (see Figure 3), clearly indicating that realistic time responses can be attained in optimized designs for a given choice of the catalyst.

After four years of activities in this research field, at the present point it is expected to carry out further work mainly on the following items:

- identification of the best compromise of carrier surface area in order to improve the effect of Zirconia on the substrate thermo-mechanical resistance and simultaneously to allow for a homogeneous impregnation by the precursor solution;
- replying the preparation of the LR-III-106 and CZ-11-600 catalysts on a carrier with lower size to reduce engine start-up transient;
- evaluating catalyst lifetime of LR-III-106 and CZ-11-600 samples with a higher value of bed load;

- optimizing the various parameters (catalyst/substrate combination and preparation, pellet size, propellant injection, decomposition pressure, bed load and pressure drop, propellant dwell time, etc.) to better fulfill typical thruster requirements.

VI. Conclusions

After four years of activities in the field of hydrogen peroxide for space propulsion, Alta S.p.A. (in collaboration with the Departments of Industrial Chemistry of Pisa and Messina Universities) has gained a solid know-how in the development of hydrogen peroxide monopropellant thrusters with advanced catalytic beds. An easily reconfigurable and expandable experimental apparatus to characterize propulsive performances of small monopropellant (peroxide) and bipropellant (peroxide-hydrocarbon) thrusters has been designed. Furthermore, the facility is assembled on a movable truck to have a high level of logistic flexibility for thruster experimental activity.

With respect to catalyst development, a novel application of Ceria-Zirconia based catalysts different from the classical automotive application has been proposed. Results widely demonstrated the positive effect on carrier strength of Zirconia addition to alumina matrix. Moreover, all the catalysts prepared by means of novel techniques displayed propulsive performances comparable to those of a commercial benchmark catalyst.

Two reconfigurable HTP monopropellant thruster prototypes have been designed and then successfully tested. For both prototypes the followed designing guidelines have allowed for step-by-step approaching a higher technical level of the device. Great improvements have been obtained in terms of start-up transient reduction with the use of an injector to atomize the hydrogen peroxide. Nevertheless further work is planned in order to correctly interface the injector with the catalytic bed.

An experimental campaign[9] has been recently carried out for investigating the performance of the LR-III-106 catalyst with a mass flux increased up to 55 kg/(m2s). The bed has shown high decomposition and propulsive efficiencies, well in excess of 90%. The cold start-up transient has been reduced to about 1 s, one order of magnitude lower than the previous obtained at lower *G*.

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