ADVANCES IN HYBRID ROCKET PROPULSION

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Abstract

This paper summarizes the strategy and the main results discussed in a series of satellite papers presented by the Space Propulsion Laboratory (SPLab) of Politecnico di Milano at the third EUCASS Conference, in the frame of the Propulsion Symposium, concerning hybrid rocket engines. SPLab has developed an intensive theoretical, experimental and numerical investigation considering different fuels, enriched with additives including metals and metal hydrides, burning under a variety of operating conditions. The ultimate objective is to select, for a variety of propulsive missions, on a relative grading, the most promising formulations. Purpose of this paper is to present significant examples of SPLab research activity, concerning the theoretical performance evaluation, the manufacture, the ballistic and the mechanical characterization of innovative solid fuel formulations, in order to obtain a rich experimental database, useful to successively validate the numerical codes developed at SPLab.

1. SPLAB STRATEGY FOR HYBRID ROCKET PROPULSION ADVANCEMENT

Peculiarities such a low-cost, safety, throttleability, and a wide range of interesting applications make hybrid rocket engines a very attractive option among the thermochemical propulsion systems. Although a long-time promise, problems such as low regression rates of the solid fuel and low combustion efficiency have so far hindered the development of large-scale hybrid rocket engines [1], [2], [3]. However some recent advances seem to suggest possible breakthroughs in the near future.

In this respect, the first task of any research activity in the field is to experimentally identify a solid fuel formulation featuring large "enough" regression rate as well as a "suitable" set of general properties (of combustion quality, mechanical properties, handling safety, cost, environmental respect, commercial availability, chemical compatibility, etc.). SPLab has developed a series of proprietary techniques to evaluate, on a relative grading, the quasi-steady regression rates of solid fuels while visualizing at the same time the flame structure. In this exploratory research program, different families of solid fuels, respectively based on HTPB and paraffin, are investigated; the influence of several additives, in terms of chemical nature and mass fraction, are analyzed; the effect of anisotropy is assessed. The ultimate objective is to select, for a variety of propulsive missions, the most promising formulations to be successively tested in details on a small-scale engine, with the important final goal to decrease the specific cost of payload delivery to space orbit. Research in the area of hybrid rocket engines is therefore focusing most on investigating the governing combustion processes, in order to achieve a better understanding and control of the peculiar phenomena involved [4], [5], and thus better performance [6], [7], [8]. Several methods have been tested in order to achieve an increase in regression rate [9], [10]; such methods can be roughly divided into chemical approaches, based on the introduction of energetic additives, fluid-dynamic approaches, based on an enhancement of the thermal exchange coefficient, and physical approaches, based on the entrainment effect. In particular, innovative solid fuels such as paraffin-based fuels [11], [12] and/or metallized fuels [13], [14] appear to be very promising in terms of enhanced regression rate. Nevertheless, further investigation is needed in order to fully understand the combustion mechanisms in a hybrid rocket engine. Currently adopted solid fuels are thermosetting polymers (e.g. derived from HTPB curing), thermoplastic materials (e.g. polyethylene) or paraffins (initially proposed at Stanford University) [15]. Addition of energetic ingredients to standard formulations (in particular nanometric metal powders) can produce interesting performance enhancement with a consequent increasing of mass burning rate. A 20 % weight addition of ultra-fine aluminum powder enhanced the fuel mass flux by 70% with respect to the corresponding nonaluminized HTPB fuel [16]. Other strategies were investigated in order to improve ballistic properties of hybrid rocket engines. Some of the tested configurations include swirled flows [17], radial injectors [18] or addition of ammonium perchlorate (AP) to the fuel [19]. Metal wires, embedded in the solid grain to increase heat transfer towards solid phase, only produced a modest gain of mass burning rate in the order of 3-4% [10]. Recently, interest in hybrid propulsion was renewed and the success of SpaceShip One in the X-Prize contest demonstrated the applicability of hybrid propulsion in reliable high-thrust rockets.

SPLab is involved in such challenging target, following a global approach to the problem. Purpose of this paper is to present significant examples of SPLab research activity, concerning the theoretical performance evaluation of innovative solid fuel formulations, their manufacture, their ballistic and mechanical characterization, in order to obtain a rich experimental database, useful to validate the numerical codes developed at SPLab. Aim of this activity is to obtain, cheaply and quickly, under different testing conditions, a relative grading of different solid fuel formulations in terms of regression rate, ignition delay, flame structure, particle emission, and radiation emission. Fuel grain samples are manufactured at SPLab, at lab-scale, and can be enriched with a variety of high-energy ingredients, ranging from uncoated or coated nano-aluminum powders to metal hydrides.

2. THEORETICAL PERFORMANCE EVALUATION

The first logical step, in the frame of SPLab strategy in hybrid propulsion, is to evaluate the theoretical rocket motor performance obtained when a new fuel composition is considered. To perform this target a thermochemical analysis is developed to investigate the specific impulse (I_s) trend. Iso-level I_s curves are built to analyze the I_s behavior according to the mixture ratio variation and the energetic material mass fraction; a typical example is shown in Fig. 1. This kind of performance estimation is obtained with the open source CEA code (Chemical Equilibrium with Applications) developed by NASA [20]. Calculation of the chemical equilibrium within the code is obtained by minimizing the Gibbs free energy.

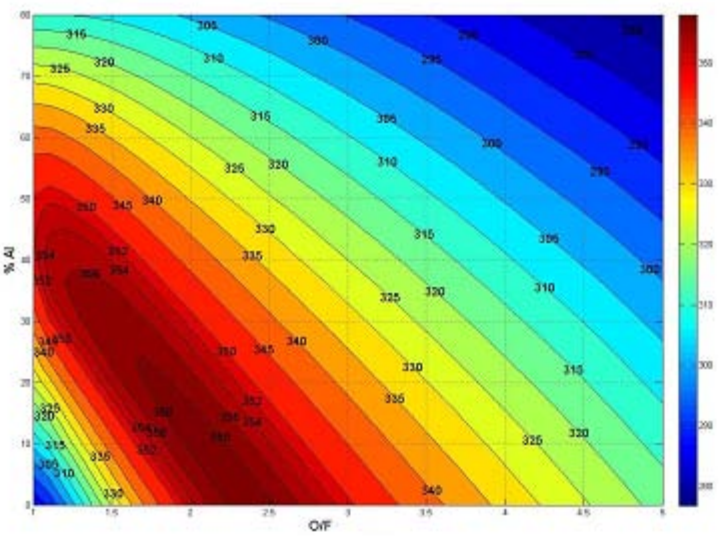


Figure 1. Specific Impulse [s] for HTPB, Al, O_2: shifting equilibrium model.
Operating conditions: chamber pressure p_c=70 bar; area ratio A_e/A_t=40.

An extensive series of formulations including several fuels and energetic materials such as polybutadiene, paraffins, aluminum, aluminum hydrides, lithium aluminum hydrides, and gaseous and/or liquid oxygen were analyzed. The theoretical analysis was carried out for frozen and shifting expansion to have a range of theoretical performance. Results, reported in [21], show that formulations with aluminum point out two opposite

trends for frozen and shifting expansion. For frozen expansion the maximum specific impulse is obtained for a relatively large percentage of aluminum (on total amount of fuel in the formulation), while for shifting expansion the maximum specific impulse is obtained without aluminum. These results highlight the importance of aluminum oxide (alumina) phase transition in the combustion products during shifting expansion, due to a phase change from solid to liquid Al_2O_3, located in the area where the highest I_s in shifting conditions is obtained.
Theoretical results obtained with frozen and shifting expansion do not consider any source of losses occurring in real propulsion systems. Nevertheless, such kind of data can be helpful to assess optimal operating conditions in order to guarantee an optimization of performance for a given formulation.

3. INNOVATIVE FUEL FORMULATION AND MANUFACTURE

The second logical step, after the theoretical fuel composition optimization, is the fuel manufacturing at lab-scale. Theoretical analyses, confirmed by experimental investigations, show that a way to improve the hybrid engine performance is to replace the traditional HTPB-based solid fuels with fuels able to form a thin, low-viscosity, and low surface tension liquid film at the regressing surface. Unstable waves and tiny droplets, produced at the tips of the waves by the interaction between the external oxidizer flow and the transversal fuel gasification, are entrained and combusted in the oxidizer flow. This atomization effect can significantly increase the regression rate of the easily liquefying fuels when compared to the traditional fuels (whether gasifying or liquefying with large viscosity). Such favorable behavior is shown by paraffin-based fuels, but unfortunately the mechanical properties of paraffin-based fuels are poor. Thus, the need arises to identify solid fuel compositions featuring at the same time suitable ballistic properties and satisfactory mechanical properties. A specific research activity was carried out at SPLab in this field; the logical evolution to increase the pure HTPB solid fuel regression rate was initially to mix HTPB and a paraffin wax. A solid paraffin wax (melting temperature, T_m = 333 K) was used, but the mixture had very poor mechanical characteristics. Liquid paraffin wax was then used in order to increase the mixture homogeneity, and thus the mechanical performance. But two main problems were immediately encountered: the entrainment effect increased negligibly and hydride addition was problematic. The last one is a particularly severe problem; it involves the "dehydrogenation" occurring when a metallic complex-hydride, for example $LiAlH_4$, is added to HTPB-resin or TIN solution. Dehydrogenation is a very dangerous phenomenon that could lead to explosions. Several improvements in fuel manufacturing allowed to solve this problem, but ballistic properties are still far from the target values interesting for a significant advancement in hybrid propulsion.

4. EXPERIMENTAL BALLISTIC CHARACTERIZATION

The third step of the chain implemented to study new fuels for hybrid propulsion concerns the experimental ballistic characterization. SPLab developed different micro-size testing facilities for hybrid rocket solid fuels combustion tests, to investigate the burning behavior of a large variety of fuel compositions.
A first facility is a radial hybrid burner, meant to measure quasi-steady regression rates under conditions similar to those of real engines. An overall sketch of this set-up is shown in Fig. 2a. The experimental rig includes a pressurized test chamber (up to 30 bar), an oxidizer feeding line and a video acquisition system for quasi-steady measurement of the solid fuel regression rate. The oxidizer is air or an O_2 + N_2 mixture, injected at the head-end of the combustion chamber. For typical operating conditions, the average chamber pressure is changed over the range 3.5 to 16 bar, the oxidizer is 100% O_2, the volumetric flow rate spans in the range 20 - 70 Nlpm. The burnt gases dump system controls the chamber pressure by a pneumatic servo system automatically driving the exhaust valves.
A cylindrical iron case (18 mm of inner diameter) accommodates an axial symmetric cylindrical solid fuel grain with a single central port. The ignition system is based on a solid propellant primer charge ignited by a CO_2 laser source located outside of the combustion chamber. Quasi-steady regression rates are measured by a proprietary video technique recognizing the burning surface position in each frame by the brightness gradient.

A second facility is the 2D slab hybrid burner, designed to investigate the combustion behavior of a new generation of hybrid solid fuels, shown in a disassembled view in Fig. 2b. This device is based on a two-dimensional slab chamber, useful to investigate the boundary layer and the flame structure, the metal powder behavior and the general development of the combustion process.

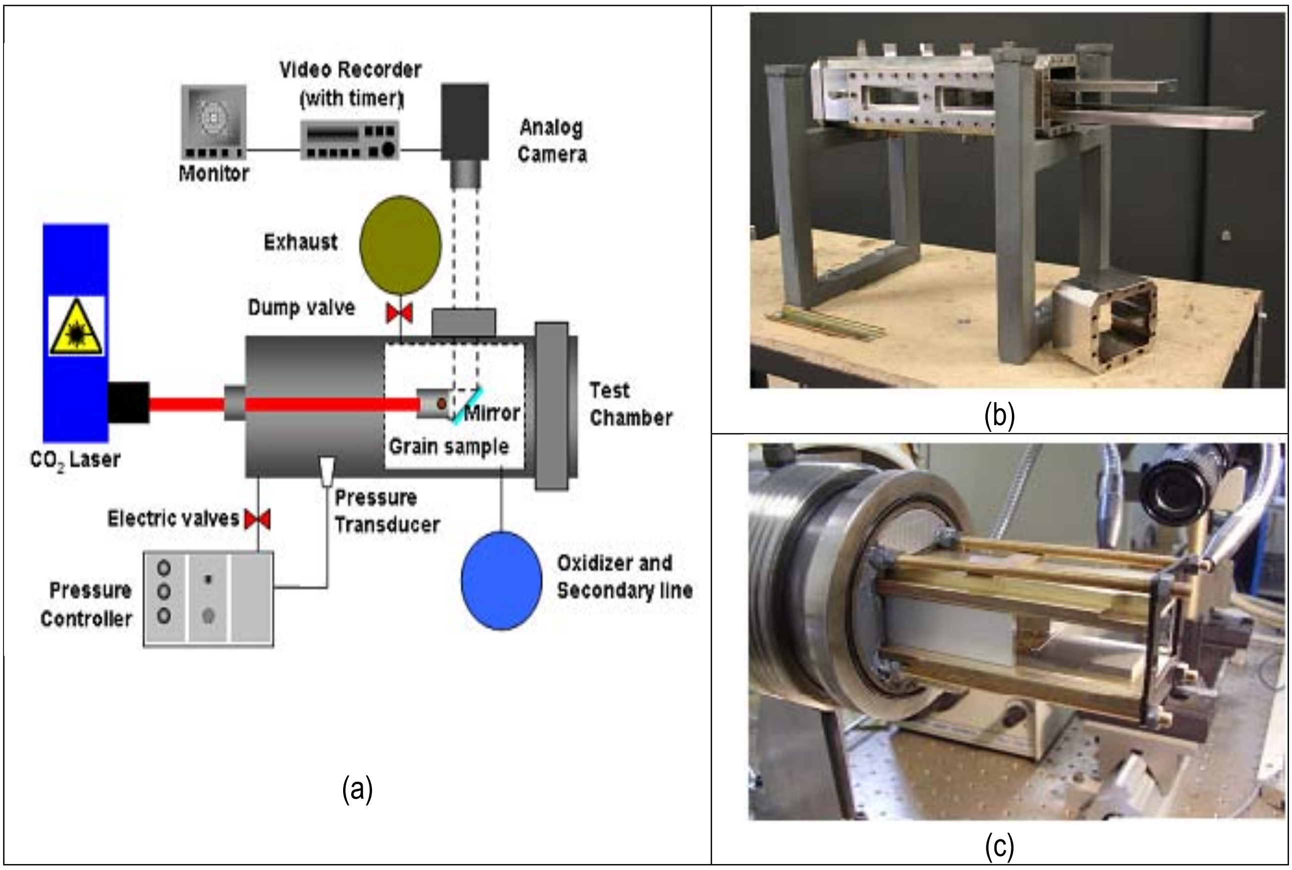


Figure 2. SPLab testing facilities.
a): overall sketch of the radial hybrid burner; b): 2D slab hybrid burner; c): detailed view of the 2D minislab hybrid burner.

The grain ignition is obtained by a pilot flame coming from the ignition of a C_3H_8/O_2 gaseous mixture or by a hot-wire technique; the oxidizer flow rate is measured by a calibrated nozzle. A special collection device allows to collect the combustion condensed residues; their analysis gives the relative combustion efficiency of different solid fuel formulations and allows to measure the condensed residues size distribution curve, useful to estimate the two-phase losses contribution for the effective specific impulse evaluation. Details are given in the companion paper [22]. The grain geometry is rectangular with a length up to 160 mm. The possibility of a detailed visualization of the grain regression surface and the complex phenomena occurring in the boundary layer represent the main advantage of this device. Video recording techniques will allow to measure the instantaneous, local regression rate along the grain surface, alternatively to the more expensive ultrasound or real-time X-ray radiography techniques.

The 2D minislab hybrid burner allows to burn a small size slab (short, minislab) of solid fuel, under hybrid configuration, under controlled pressure and oxidizer flow. The difference with respect to the previously described burners is the capability to observe the details of the resulting flame with high-resolution video-recording. Solid fuel samples of rectangular shape (15 x 22 x 4 mm) are arranged in a rectangular cross section chamber (32 x 24 mm, 100 mm long) with lateral windows allowing visualization of the combustion process. Fuel samples were ignited using a hot wire; pressure was kept constant during the combustion test by means of an automatic pressure control system. The radiant energy, emitted during combustion, was measured by means of a micro-calorimeter, put on the top of the chamber. Details of the experimental set-up are shown in Fig. 2c.

.1 Representative results in the radial hybrid burner

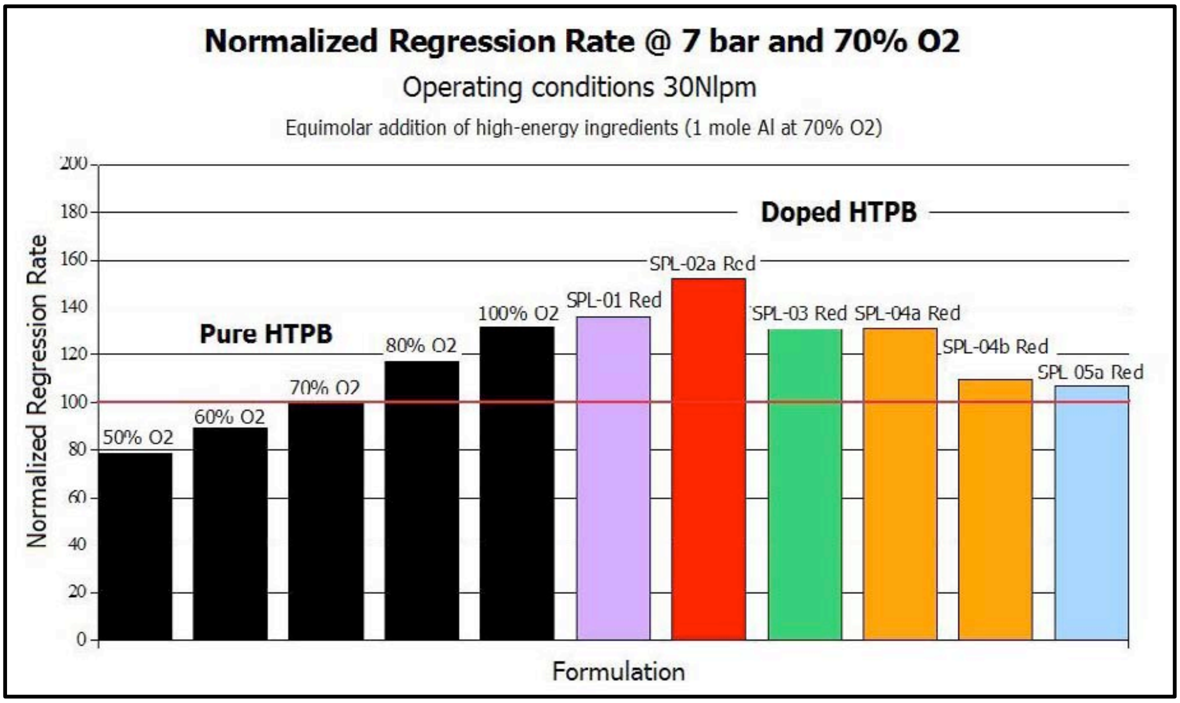


Figure 3a. Normalized regression rates for a variety of HTPB-based solid fuels at 7 bar and 70% O_2.

Representative results obtained in the radial hybrid burner facility are illustrated in Fig. 3a (overall trend under the specified operating conditions) and Fig. 3b (effect of MgH_2 addition to HTPB under the specified operating conditions. With respect to pure HTPB, the MgH_2 addition (10% of the total mass) allows to increase the regression rate by 62% at 7 bar and 33% at 10 bar at the largest oxidizer mass flux investigated in this case.

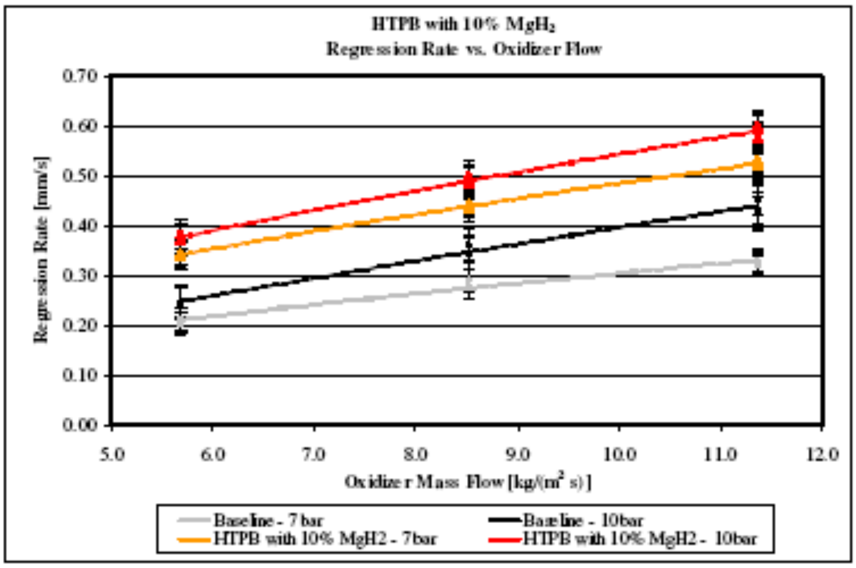


Figure 3b. Regression rate vs. oxidizer mass flow rate for HTPB loaded with 10% MgH2 , burning under reference conditions at 7 and 10 bar. Oxygen fraction: 50 %. Each operating point defined by 3 tests.

Regression rate [@ 7 bar, data fitting ($R^2 = 0.988$)]: $r_f = (0.117 \pm 0,04)\ G^{(0.617 \pm 0.015)}$

Regression rate [@ 10 bar, data fitting ($R^2 = 0.988$)]: $r_f = (0.112 \pm 0,05)\ G^{(0.648 \pm 0.020)}$

.2 Representative results in the 2D slab hybrid burner

An example of the average regression rate, measured in the 2D slab hybrid burner, for six fuel formulations (Table 1), obtained at four selected oxygen mass fluxes (indicated in the figure caption), is reported in Fig. 4.

Table 1. Fuel formulation, Al grain size, fuel density and regression rate.

Fuel formulation	Nominal average metal particle size (μm)	Average fuel density (g/cm^3)	Regression rate vs. Oxidizer mass flux
Pure HTPB	--	0.929	$r_b = (0.028 \pm 0.002)\ G^{0.48 \pm 0.02}$
HTPB 50% + LP 50%	--	0.898	$r_b = (0.026 \pm 0.002)\ G^{0.52 \pm 0.03}$
HTPB 45% + LP 45% + μAl 10%	30 (Al_05)	0.963	$r_b = (0.016 \pm 0.008)\ G^{0.50 \pm 0.15}$
HTPB 45% + LP 45% + MgH_2 10%	50-150	0.934	$r_b = (0.010 \pm 0.002)\ G^{0.68 \pm 0.04}$
HTPB 45% + LP 45% + nAl 10%	0.28 (Al_04b)	0.963	$r_b = (0.008 \pm 0.002)\ G^{0.76 \pm 0.06}$
HTPB 90% + nAl 10%	0.28 (Al_04b)	0.992	$r_b = (0.011 \pm 0.004)\ G^{0.65 \pm 0.10}$

Comparing the results obtained for the different oxygen mass fluxes tested (19, 30, 65 and 95 kg/m^2s), one can observe regression rate increases for all the tested formulations, when the oxidizer mass flux increases. The two formulations filled with the nano-powder (HTPB+LP+nAl and HTPB+nAl) show the higher increase.

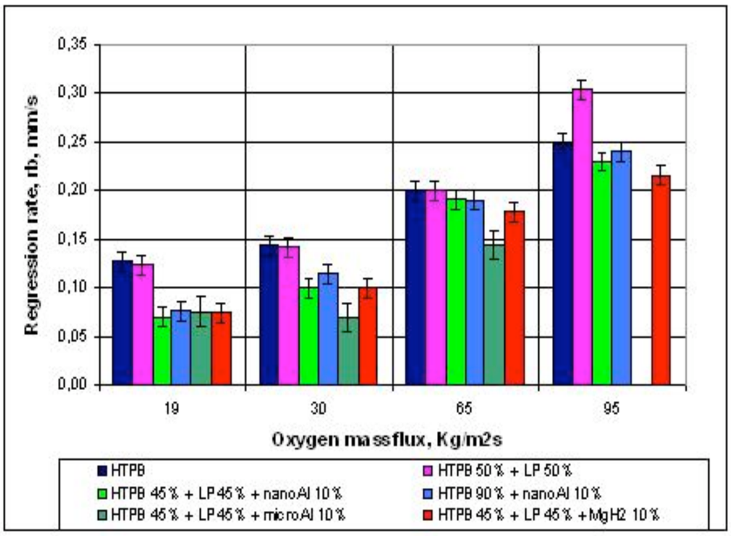


Figure 4. Regression rate results for the selected fuel formulations. Tests performed at 19, 30, 65 and 95 kg/m^2s oxygen mass flux. μAl formulation tested only up to 65 kg/m^2s.

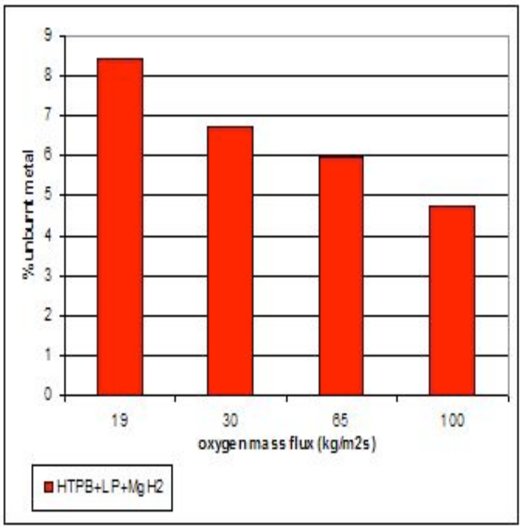


Figure 5. Percentage of unburnt metal over the metal content, as a function of oxygen mass flux, for the magnesium hydride filled formulation.

At 19 kg/m^2s the four metallized formulations show similar regression rate values (within the experimental error). At 30 and 65 kg/m^2s the nAl filled formulations show higher regression rates than that of the μAl filled formulation. MgH_2 formulation (coarse metal particles but high reactivity due to the hydride) shows only slightly worse performance than nAl filled formulations. HTPB+LP and pure HTPB formulations regression rate increases are of 50% and 20%, respectively, when O_2 flux increases from 65 to 95 kg/m^2s. This is likely to be a consequence of the entrainment effect.

Figure 5 shows the results of the metal combustion efficiency estimated for a HTPB + LP + MgH2 fuel. The unburnt metal fraction decreases when the oxygen mass flux increases.

.3 Some results in the 2D minislab hybrid burner

The 2D minislab hybrid burner was used to measure the radiant energy flux from the flame and the combustion products of solid fuels designed for hybrid rockets; to perform this task a “home made” improved version of Zenin’s micro-calorimeter [23] was implemented. The radiant energy flux was measured for fuel samples formulations ranging from nonmetallized (pure HTPB and HTPB + paraffin-based), to a mildly metallized (Al 5%) to a heavily metallized (Al 15%). This study pointed out the fundamental role of soot, originated by HTPB pyrolysis. A lower amount of soot during the combustion of fuels containing a lower HTPB mass fraction, is the reason of a significantly lower radiant energy emission.

5. EXPERIMENTAL MECHANICAL CHARACTERIZATION

The challenge for more performing hybrid fuels has also to compete with appropriate mechanical properties. Research roadmap has to deliver materials with interesting combustion features as well as mechanical behavior capable of real-world applications. This is the focus of research activity on fuel mechanical properties at the SPLab. Activity here documented is relevant to stress-strain curves under tensile testing condition which grant the evaluation of fundamental properties such as elastic modulus, rupture conditions, behavior at different strain rates and so on. Such testing is performed using dog-bone samples shaped according to the standard DIN 53504 S3A and testing facilities available at the Department of Aerospace Engineering of Politecnico di Milano. Other activities regarding dynamic mechanical properties are also performed while studies on material aging are planned for the future.

A current trend for hybrid fuel formulation is the use of paraffin inside the fuel as a promoter of entrainment effect and, thus, bearer of a higher regression rate. As mentioned before in brief, liquid paraffin was added to the polymer aiming to entrainment effect in conjunction with good mechanical features.

As an example, the tangent elastic modulus is shown in Fig. 6 for the following four formulations:

- HTPB-based binder;
- 50% HTPB + 50% liquid paraffin binder (labeled as PH);
- HTPB-based binder + 10% μAl filler;
- 50% HTPB + 50% liquid paraffin + μAl filler (labeled as P-Al).

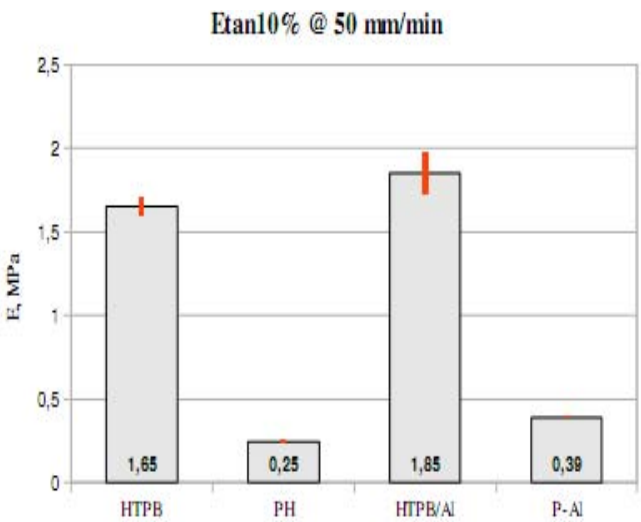


Figure 6. Tangent elastic modulus at 10% (ASTM 111) for different formulations, metallized or not.

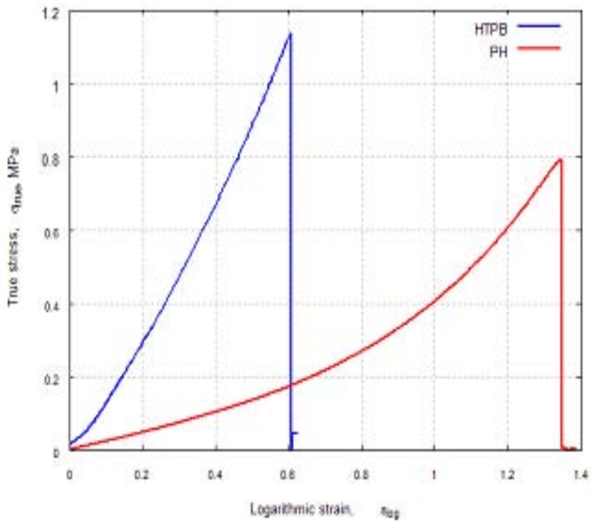
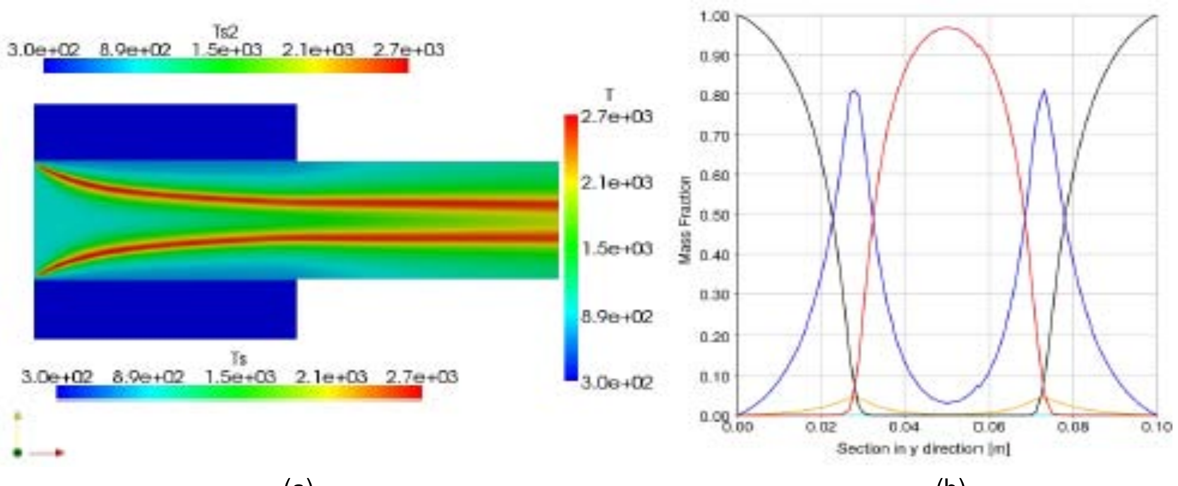


Figure 7. True stress vs. logarithmic strain for HTPB- four based and HTPB-paraffin mixed formulations.

The formulation made of HTPB and paraffin, despite being very soft, can stretch more than twice the original composition with a limited loss of maximum stress. Two curves, obtained in a test at a speed of 50 mm/min, are reported in Fig. 7 as an example.

5 NUMERICAL SIMULATION ACTIVITIES

Numerical simulation activities performed at SPLab aim to develop a numerical code of the combustion processes in hybrid rocket motors [24], after the pioneering work by Marxmann et al. [25]. The code follows a multiphysics approach, with a coupling between pyrolysis, which concerns the solid fuel grain degradation, and the combustion processes that take place in the turbulent boundary layer over the solid fuel grain surface [26]. The code is implemented in the opensource OpenFOAM code [27]. OpenFOAM is a finite volume code, with integral approach based on the integration of the governing partial differential equations.
Two different computational domains are considered: the first concerning the combustion chamber and the second one the solid fuel grain. In the first domain a numerical simulation of turbulent combustion with RANS (Reynolds Averaged Navier Stokes) approach and WSR (well stirred reactor) closure for the reaction rate term is developed. Mass and energy balances at the interface between solid and gas region are considered to study the grain pyrolysis and the entry of fuel vapors in the gas region. This blowing effect is not treated as boundary condition but as a consequence of the fuel solid grain pyrolysis. The regression rate equation is written with the Arrhenius law.
Regression rate, temperature and species behaviors can be plotted for different sections of the domain during the simulation time. Several parametric studies were performed to analyze boundary conditions, geometry, and chamber size influence. Changes in inlet velocity, oxygen inlet temperature, pressure and domain dimensions were analyzed. Low influence of pressure was highlighted; large influence of the flow on the whole combustion process, through the momentum exchange, is confirmed. If inlet velocity increases, the flame takes place in the post combustion chamber and an oscillation trend can be observed. If the oxygen inlet temperature decreases, an ignition delay is observed; the flame does not start at the boundary edge of the grain but moves more than a half of the grain. If the domain dimensions are reduced, an interaction between the flame and the wall is observed. Moreover, a study on the influence of radiation was carried out, introducing in the code an appropriate model of radiation. The comparison between results obtained with or without radiation highlights the importance of radiation in the combustion of hybrid rocket motors. A decrease in the flame temperature and an increase in the surface grain temperature results in increased regression rate.
Results of Fig. 8 show the temperature field and the species concentration profiles at a cross section of a 2D slab chamber, located at 45% of the grain length.



(a) (b)

Figure 8. Numerical simulation results for a 2D slab combustion chamber. A k-ε turbulence model, a four reactions kinetic scheme and a radiation model are taken into account. (a): temperature field; the blue regions represent the two solid fuel grains; (b) species concentration profiles at a cross section of the chamber located at 45% of the grain length.

Work is in progress to develop a code, validated on the experimental database available at SPLab, capable to predict the trends governing hybrid rocket motors combustion processes.

6. CONCLUSIONS AND FUTURE DEVELOPMENTS

In the framework of the renewed international interest in hybrid rocket propulsion, due to peculiarities such a low-cost, safety, throttleability, and a wide range of interesting applications, SPLab of Politecnico di Milano has been working on a global approach aiming at investigating innovative solid fuels for a new generation of hybrid rockets. Theoretical, experimental and numerical activities were implemented. Nano-metallized, paraffin-based, metal-hydrides based fuels were proposed and investigated. Theoretical performance evaluations were analyzed. Manufacturing procedures were developed and specific protocols were tuned for the solid fuel preparation. Simple and effective experimental approaches were designed to characterize several new hybrid solid fuels; micro-sized set-ups were realized to quickly investigate the combustion behavior of different solid fuels compositions in terms of regression rate. Further activities were performed according to the same above mentioned criteria (low-cost and low-time consuming), for the measurement of ignition delay and radiant energy emission during combustion. The experimental characterization of selected formulations also involved a study of the main mechanical properties. Numerical simulation activities were developed with the opensource OpenFOAM software package, linked to the experimental SPLab activities.

Pure HTPB-based fuels, as well as paraffin-based and metallized fuels were taken into account and some selected, corresponding results were presented in this paper as representative examples.

Future work will focus on investigating the effects of additives in HTPB-based fuels with special attention to ultra-fine aluminum powders and metal-hydrides, and to the general behavior of the promising yet still puzzling paraffin-based fuels.

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REFERENCES

[1] N.A. Davydenko, R.G. Gollender, A.M. Gubertov, V.V. Mironov, and N.N. Volkov, Hybrid Rocket Engines: The Benefits and Prospects, Aerospace Science and Technology, 11, 55–60, 2007.

[2] C. Oiknine, New Perspectives for Hybrid Propulsion, 42nd AIAA Aerospace Sciences Meeting and Exhibit, AIAA 2006-4674, Sacramento, California, 9 - 12 Jan 2006.

[3] D. Altman, Highlights in Hybrid Rocket History, The 8th International Workshop on Combustion and Propulsion, 8-IWCP, Rocket Propulsion: Present and Future, Naples, June 2003.

[4] A. Gany, G. Manheimer-Timnat, and M. Wolfshtein, Two-Phase Flow Effects on Hybrid Combustion, Acta Astronautica, 3, 241-263, 1976.

[5] M.J. Chiaverini, K.K. Kuo, A. Peretz, and G.C. Harting, Regression-Rate and Heat-Transfer Correlations for Hybrid Rocket Combustion, Journal of Propulsion and Power, 17(1), pp. 99-110, 2001.

[6] M.J. Chiaverini, N. Serin, D.K. Johnson, Y.C. Lu, K.K. Kuo, and G.A. Risha, Regression Rate Behavior of Hybrid Rocket Solid Fuels, Journal of Propulsion and Power, 16(1), 125-132, 2000.

[7] G.A. Risha, A. Ulas, E. Boyer, S. Kumar and K.K. Kuo, Combustion of HTPB-based Solid Fuels Containing Nano-sized Energetic Powder in a Hybrid Rocket Motor, 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, AIAA 2001-3535, Salt Lake City, Utah, 8 - 11 Jul 2001.

[8] B. Evans, N.A. Favorito, E. Boyer, G.A. Risha, R.B. Wehrman, and K.K. Kuo, Characterization of Nano-Sized Energetic Particle Enhancement of Solid-Fuels Burning Rates in an X-Ray Transparent Hybrid Rocket

Engine, 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, AIAA 2004-3821, Fort Lauderdale, Florida, 11 - 14 Jul 2004.

[9] B.J. Evans, N.A. Favorito, and K.K. Kuo, Oxidizer-Type and Aluminum-Particle Addition Effects on Solid-Fuel Burning Behavior, 42nd AIAA JPC & Exhibit, AIAA 2006-4676, Sacramento, California, Jul 2006.

[10] K.H. Shin, C. Lee, and S.Y. Chang, The Enhancement of Regression Rate of Hybrid Rocket Fuels by Various Methods, 43rd AIAA Aerospace Sciences Meeting and Exhibit, AIAA 2005-0359, Reno, Nevada, 10 - 13 Jan 2005.

[11] M.A. Karabeyoglu, B.J. Cantwell, and D. Altman, Development and Testing of Paraffin-based Hybrid Rocket Fuels, 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, AIAA 2001-3535, Salt Lake City, Utah, 8 - 11 Jul 2001.

[12] M.A. Karabeyoglu, D. Altman, and B.J. Cantwell, Combustion of Liquefying Hybrid Propellants: Part 1, General Theory, Journal of Propulsion and Power, 18(3), 610-620, 2002.

[13] G.A. Risha, E. Boyer, R.B. Wehrman, and K.K. Kuo, Performance Comparison of HTPB-Based Solid Fuels Containing Nano-Sized Energetic Powder in a Cylindrical Hybrid Rocket Motor, 37th AIAA/ASME/ SAE/ ASEE Joint Propulsion Conference and Exhibit, AIAA 2002-3576, Salt Lake City, UT, 8 - 11 Jul 2001.

[14] G.A. Risha, B.J. Evans, E. Boyer, R.B. Wehrman, and K.K. Kuo, Nano-Sized Aluminum- and Boron-based Solid Fuels Characterization in a Hybrid Rocket Engine, 39th AIAA/ASME/SAE/ASEE JPC & Exhibit, AIAA 2003-4593, Huntsville, AL, 20 - 23 July 2003.

[15] M.F. Karabeyoglu, B.J. Cantwell, and J. Stevens, Evaluation of Homologous Series of Normal-Alkanes as Hybrid Rocket Fuels, 41st AIAA/ASME/SAE/ASEE JPC & Exhibit, Tucson, AZ, 10-13 Jul 2005. AIAA 2005-3908.

[16] G.A. Risha, E. Boyer, R.B. Wehrman, and K.K. Kuo, Performance Comparison of HTPB-Based Solid Fuels Containing Nano-Sized Energetic Powder in a Cylindrical Hybrid Rocket Motor, 38th AIAA/ASME/ SAE/ ASEE Joint Propulsion Conference and Exhibit, Indianapolis, IN, 7-10 Jul 2002. AIAA 2002-3576.

[17] S. Yuasa, O. Shimada, T. Imamura, T., Tamura, and K. Yamamoto, A Technique for Improving the Performance of Hybrid Rocket Engines, 35th AIAA/ASME/SAE/ASEE JPC & Exhibit, AIAA 1999-2322, Los Angeles, CA, 20-24 Jun 1999.

[18] C. Carmicino and A. Russo Sorge, Influence of a Conical Axial Injector on Hybrid Rockets Performance, Journal of Propulsion and Power, 22(5), 984-995, 2006.

[19] P. George, S. Krishnan, P.M. Varkey, M. Ravindran and L. Ramachandran, Fuel Regression Rate in HTPB/Gaseous-Oxygen Hybrid Rocket Motors, Journal of Propulsion and Power, 17(1), 35-42, 2001.

[20] CEA, http://www.grc.nasa.gov/www/CEAWeb/

[21] G. Gariani, F. Maggi, L. Galfetti, Numerical Analysis of the Specific Impulse for Hybrid Fuel with Energetic Materials, Associazione Italiana di Aeronautica ed Astronautica, XX Congresso AIDAA 2009, Milano, 29 June - 3 July 2009. Accepted for presentation.

[22] L. Merotto, M. Boiocchi, L. Galfetti, G. Colombo and L.T. De Luca, Regression Rate Measurement of Hybrid Rocket Metallized Solid Fuels: Influence of Oxidizer Mass Flux and Pressure, XX AIDAA 2009, Milano, 29 June - 3 July 2009. Accepted for presentation.

[23] A.A. Zenin, A.P. Glazkova, O.I. Leipunskii and V.K. Bobolev, Microcalorimeter Measurements of Flame Emission, Combustion Explosion and Shock Waves, 4(2), 196-202, 1968.

[24] G. Gariani et al, 2D Numerical Simulation of Combustion Processes in a Slab Hybrid Rocket Motor, 3rd EUCASS Conference, Versailles, 6 – 10 July 2009. Accepted for presentation.

[25] G. Marxman, and M. Gilbert, Turbulent Boundary Combustion in The Hybrid Rocket, 9th International Symposium on Combustion, 1337–1349, 1962.

[26] T. Poynost, and D. Veynante, Theoretical and Numerical Combustion, Edwards, Philadelphia, 2005.

[27] OpenCFD, http://www.opencfd.co.uf/openfoam/