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Characterization of HTPB-based solid fuel formulations: Performance, mechanical properties, and pollution

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ABSTRACT

Features such as safety, low-cost, and throttleability make hybrid rocket engines an attractive option for suborbital flights and space exploration missions in general. While the domain of possible liquid oxidizers is well characterized, the choice of a suitable solid fuel is still a matter of investigation. Space Propulsion Laboratory (SPLab) at Politecnico di Milano has developed a series of proprietary techniques to evaluate, on a relative grading, the quality of innovative solid fuels while visualizing at the same time their flame structure. But a serious alert was recently notified that soot emission from hydrocarbon fuels has the potential to contribute to global climate change. In this paper, HTPB polymer has been taken as baseline and characterized at laboratory level in terms of ballistic properties, mechanical testing, and thermochemical calculations.

1. Background

The perspective of space launch activities is presumably changing within few years. Past and current activities are mostly hold by governmental institutions but space tourism on one hand and the uncertainties related to future USA space manned missions (after Space Shuttle retirement) on the other, strengthen the position of private firms (such as Virgin Galactic, Xcor, Armadillo Aerospace, Blue Origin, Dassault, and others). As of now, suborbital flights for tourism and scientific research are likely to represent the major part of this market in the near and medium term future. Indeed several projects are currently under development, looking at the possibility to share a demand of about one thousand launches per year, once the market is fully developed [1].

Space tourism was started by Mr. Dennis Tito ten years ago, with an orbital mission combining Soyuz TM-32, ISS-EP1, and Soyuz-TM-31 for almost 8 days at $20 million in April 2001. Since then it has extended to suborbital flights: SpaceShipOne by Mojave Aerospace Ventures won the Ansari X Prize of $10 million in October 2004. Meanwhile a range of appealing new projects materialized, including lunar flyby tours (Space Adventures, two seats per flight offered at $150 million each), space stations (Space Adventures selling flights to ISS for $20 million/passenger and the recent Excalibur Almaz by Jurby), space hotels (Bigelow Aerospace), and so on. In particular, suborbital space tourism is expected to be a $700 million industry by 2020, flying thousands of passengers a year to the near zero gravity of the outer space edge. Projects are being developed not only in USA but also by Dassault, EADS Astrium, and Project Enterprise (Black Sky spaceplane) in Europe; other initiatives were notably triggered in Russia and Japan. Overall, private human access to space represents an incredible opportunity for aerospace industry.

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The most ambitious project is SpaceShipTwo by Virgin Galactic, whose objective is to realize a massive program of commercial suborbital flights to paying passengers (space tourism) by running a world-wide fleet of vehicles. Each spaceship (one hybrid rocket engine) will run twice a day while the carrier plane (four jet engines) will run up to four times a day. For each flight SpaceShipTwo will accommodate two pilots and six passengers at $200,000 per seat. By reaching 110 km altitude, the passengers will enjoy about 5 min of reduced gravity. Within few years, a total of 50 carrier planes are expected to be operated for space tourism, orbit injection of small satellites, and more.

Hybrid rocket propulsion is a good candidate for the above kind of applications, being safer and more performing than solid propellants in terms of gravimetric specific impulse, less expensive than liquid propellants in terms of development and management of the propulsive system, and (at least claimed to be) environmentally-friendly. Mainly for its intrinsic safety and low-cost features, hybrid rocket propulsion is specially suited for private human access to space. For hybrid rocket propulsion, the option is available to select the best ingredients already known from liquid and solid rocket propulsion. The choice of liquid oxidizer heavily affects the whole propulsive system design, but the related technology is well characterized thanks to the huge expertise collected during last decades from liquid rocket propulsion. On the contrary, solid fuel technology for hybrid propulsion still requires improvements. Limitations are indeed still faced, such as low regression rate and combustion inefficiency, causing unproven capability of large rocket operations. Overall, the low readiness level of hybrid propulsion, evaluated between 2 and 3 for large-scale engines, is still a significant drawback. Therefore, intense research activities are currently ongoing in this field [2].

The current work presents a complete laboratory investigation on solid fuels based on the HTPB polymer (taken as a nonmetallized baseline). Although paraffin-based solid fuels allow much larger regression rates (with the penalty of poor mechanical properties), HTPB or other polymers are commonly used in several projects: HTPB/N_2O in Mojave Aerospace Ventures SpaceShipOne, again HTPB/N_2O in Virgin Galactic SpaceShipTwo, HTPBc (containing a small amount of some unspecified particle fillers)/87.5% H_2O_2 in Nammo, epoxy/N_2O in Copenhagen Suborbitals HATV or polyurethane/LOX in Copenhagen Suborbitals HEAT, etc. Thermochemical analyses suggest that HTPB binder can profitably be used as a solid fuel in hybrid rockets, granting higher specific impulse with respect to solid propulsion. Nevertheless, the realization of expected performance enhancement requires the knowledge of all interleaving phenomena occurring during the combustion and, thus, a full characterization is required.

Ballistic and mechanical properties will be presented and critically analyzed. Moreover, considering the discussions triggered by a recent paper by Ross et al. [3] on hybrid rocket environmental impact, an analysis of pollutant emissions will be conducted through calculations made under ideal assumptions. Focus will primarily be posed on carbon black as the responsible of potential climate changes, while considering four different potential oxidizers in the perspective of small-scale motor testing for real applications in the field of space tourism.

2. Experimental ballistics

Two hybrid burners were designed to enable relative ballistic grading of different fuel formulations and are currently in use at SPLab: a 2D radial setup suitable for time-resolved quasi-steady ballistics and a 2D slab setup suitable for boundary layer analyses and flow field visualization.

The simple SPLab 2D radial burner enables a continuous tracking of the solid fuel gasifying surface during test at the visible sample cross-section. Therefore, for the visualized section, time-resolved regression rate can be achieved with a simple and low-cost experimental setup.

Several tests for HTPB fuel burning in GOx were investigated to assess the quality of the proposed technique, even under transient conditions. Fuel was prepared starting from HTPB R45 resin cured by IPDI, using DOA as plasticizer and Dibutyltin Diacetate as curing catalyst. A degas cycle of the fuel formulation before molding of the samples grants realization of strands with high quality and porosity lower than 1%.

The main task is to experimentally identify a solid fuel formulation featuring adequate steady regression rates and short settling times in case of transient operations. In this framework, SPLab has developed a series of proprietary techniques to evaluate the quasi-steady ballistics of solid fuels, including regression rates, while visualizing at the same time their flame structure.

2.1. Experimental facility: 2D-radial burner

A schematic overview of the implemented 2D-radial (micro) burner is shown in Fig. 1. The combustion chamber is a stainless steel cylinder housing the injector head and optical accesses for test visualization. The main observable of interest is the regression rate of the single perforation cylindrical solid fuel sample. During combustion the burning cross-section of the tested fuel is fully visible thanks to a proper combination of lateral windows and a 45 degree mirror placed inside the combustion chamber. The regression rate can therefore be monitored by an optical technique tracking the gasifying surface history of the fuel grain all along the combustion process [4–7].

Both oxidizer mass flow and chamber pressure of the test rig can be regulated independently, thus allowing different test conditions to be easily explored.

The oxidizer is fed by cylinders and is injected through a number of holes realized in the internal surface of the sample holder, thus providing control on the nature of the flow investing the fuel sample. Both axial and swirled oxidizer flowing over the tested fuel surface can be achieved; the latter is commonly employed. The oxidizer is delivered to the injector by a dedicated primary feed line instrumented with measuring and controlling hardware for the mass flowing through the central port and