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An Italian network to improve hybrid rocket performance: Strategy and results ☆

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ABSTRACT

The new international attention to hybrid space propulsion points out the need of a deeper understanding of physico-chemical phenomena controlling combustion process and fluid dynamics inside the motor. This research project has been carried on by a network of four Italian Universities; each of them being responsible for a specific topic. The task of Politecnico di Milano is an experimental activity concerning the study, development, manufacturing and characterization of advanced hybrid solid fuels with a high regression rate. The University of Naples is responsible for experimental activities focused on rocket motor scale characterization of the solid fuels developed and characterized at laboratory scale by Politecnico di Milano. The University of Rome has been studying the combustion chamber and nozzle of the hybrid rocket, defined in the coordinated program by advanced physical-mathematical models and numerical methods. Politecnico di Torino has been working on a multidisciplinary optimization code for optimal design of hybrid rocket motors, strongly related to the mission to be performed. The overall research project aims to increase the scientific knowledge of the combustion processes in hybrid rockets, using a strongly linked experimental–numerical approach. Methods and obtained results will be applied to implement a potential upgrade for the current generation of hybrid rocket motors. This paper presents the overall strategy, the organization, and the first experimental and numerical results of this joined effort to contribute to the development of improved hybrid propulsion systems.

1. Introduction

The aim of this research project is to build an Italian scientific community focused on theoretical, experimental and numerical activities aimed to the improvement of hybrid rocket propulsion technology for the space access and exploration. The project consists in a two-year long work developed in such a way as to optimize the available budget.

Combustion processes represent the key problem in the development of the hybrid rocket design. The growing international attention to hybrid propulsion points out that the hybrid rocket propulsion system design needs of the understanding of physico-chemical phenomena that control the combustion process and of the fluid dynamics inside the motor. The knowledge of the complex interactions among fluid dynamics, solid fuel pyrolysis, oxidizer atomization and vaporization (in case of liquid oxidizer), mixing and combustion in the gas phase, particle formation, and radiative characteristics of the gas and the flame can only be improved by combined experimental and numerical research activities. Similar considerations can be made in the ablation process of the nozzle thermal

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Nomenclature

A_b	sample burning area, m^2
B	boundary layer blowing parameter
c^*	characteristic velocity, m/s
E_j	activation energy, kJ/mol
h	thickness of the melt layer at the fuel surface, mm
G	mass flux, kg/m^2 s
m	mass, g
m_{ent}	entrainment component of mass flux from fuel surface, kg/m^2 s
p_d	dynamic pressure, Pa
r_f	solid fuel regression rate, mm/s
t_b	combustion time, s
T	temperature, K
μ	cinematic viscosity, mPa/s
ρ	solid fuel density, kg/m^3
σ	surface tension, mN/m
Φ	equivalence ratio $(O/F)/(O/F)_{stoichiometric}$
CB	carbon black
GOX	gaseous oxygen
HP	hydrogen peroxide, H_2O_2
GW-	gel wax-based fuels group
HTPB	hydroxyl-terminated poly-butadiene
LOX	liquid oxygen
H-	HTPB-based fuels group
KER	kerosene
MA	maleic anhydride
MMH	mono methyl hydrazine, $CH_3N_2H_3$
MO	mineral oil
PE	polyethylene
NTO	nitrogen tetroxide, N_2O_4
PUF	poly urethane foam
SEBS	styrene–ethylene–butadiene–styrene
SW-	solid wax-based fuels group
TPE	thermoplastic polymers
UDMH	unsymmetrical dimethil hydrazine, $(CH_3)_2N_2H_2$

protection. The numerical study of the flow in the combustion chamber and in the nozzle of a hybrid rocket requires careful handling of the interaction between the reacting flow and the solid surface.

This project includes four research units: Politecnico di Milano (PoliMi), Università degli Studi di Napoli "Federico II" (UniNa), Università di Roma "La Sapienza" (UniRoma) and Politecnico di Torino (PoliTo).

The objective of the experimental activity performed by PoliMi is the development of innovative solid fuels for hybrid propulsion, characterized by higher regression rates in comparison to the more traditional fuels currently used. The aim of the investigation is to achieve a regression rate increase up to 3–4 times higher than the current values. Such an increase has been achieved with liquefying fuels, but the unacceptable mechanical properties of the grain after ignition make it unsuitaible for use. Further investigation of innovative formulations is therefore needed. The aim of this research program is also to face the problem of paraffin-based liquefying fuels mechanical properties. Innovative fuel formulations development, and their experimental characterization provide a set of experimental data useful for development and validation of the numerical codes developed by PoliMi, UniRoma and PoliTo units.

UniNa research unit is involved in firing tests of fuel formulations characterized on lab-scale by PoliMi in a hybrid rocket motor. Tests are carried out with several chamber pressures and oxidizer mass fluxes, and different fuel compositions. Furthermore, the motor thrust, the characteristic exhaust velocity c^*, the corresponding efficiency, chamber pressure and the fuel consumption spatial distribution are measured in order to collect useful design parameters and to compare the data with the theoretical models concerning the injection and fuel composition influence on regression rate, combustion efficiency and stability. Data referred to the flow conditions at the nozzle inlet (p,T,O/F) are given to UniRoma in order to allow the nozzle environment characterization and the thermal protection behavior evaluation. The final output will be the motor characterization and the achievement of a deeper knowledge on the hybrid motors operation.

UniRoma′s objective is to study the combustion chamber and nozzle of hybrid rockets by means of physico-mathematical models and numerical methods. This, in turn, requires the knowledge of the complex interactions between fluid dynamics, the process of solid fuel pyrolysis, the atomization and vaporization of the oxidizer (if liquid oxidizer is considered), mixing between oxidizer and fuel, combustion in the gas phase, particulate formation, and radiative characteristics of the gas and flame. In a classical hybrid propellant rocket, the liquid or gaseous oxygen injected into the ports of solid fuel grain (typical fuel is HTPB) reacts in the combustion chamber with the pyrolysis gas, which is produced on the surface and diffuses into the boundary layer, forming a turbulent diffusion flame. The solid fuel in a hybrid rocket regresses slowly making, in fact, necessary to use a large fuel surface exposed to hot gas to get the mass flow rate required by the motor design. Classical studies on hybrid propulsion are based on simplified models of the boundary layer to derive the heat flux to the surface of the solid fuel and, consequently, its regression rate. However, this simplified analysis cannot take into account many of the complex chemical and physical interactions among the various processes, making necessary to develop more advanced models based on computational fluid dynamics (CFD) to improve prediction and analysis capabilities for such propulsion systems.

The main objective of PoliTo research unit is to develop a multidisciplinary optimization (MDO) procedure for hybrid rocket motors which joins the optimization of propulsion system design parameters and trajectory. The intrinsic interaction between propulsion system performance and