Analysis of Fluid-dynamic Systems to Increase Combustion Efficiency in Hybrid Rockets

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Abstract:

This paper presents a summary of the activities conducted at CISAS "G. Colombo" and University of Padua to analyse various possible methods aimed at increasing combustion efficiency.

Combustion efficiency in standard hybrid rocket motors is usually low. This is due to the poor mixing of the core oxidizer flow with the gasified fuel entering the grain port from the fuel walls. Motor scale up usually worsens this issue. Large and volumetric inefficient post combustion chambers are common devices used to improve efficiency, while mixers are somewhat more complex, but more effective devices.

Two main paths have been followed to obtain such a goal: the use of special devices in the combustion chamber, like diaphragms and mixers and a modification of the injection sub-system.

The species mixing enhancement can be achieved using a diaphragm, which can be introduced at different locations inside the combustion chamber. Simple 1-hole diaphragms at different locations in terms of fuel grain length have been tested, but also 4-hole diaphragms in different positions have been investigated. The centre-hole diameter has been optimized. Moreover, CFD simulations have been carried out to further understand the consequences triggered by the chemical species enhanced mixing. N_2O was selected as the oxidizer and paraffin Sasol Wax 0907 as the fuel.

Various CFD analyses have been performed to compare the combustion efficiency of the basic rocket geometry, to the efficiencies showed by the motor configurations having a one-hole or a 4-hole diaphragm placed at different locations along the combustion chamber. The results have been compared to the corresponding experiments, in order to prove that CFD can correctly predict global hybrid motor performance and that it is a good design tool, helping the choice of the most appropriate rocket configuration in each specific case. These numerical analyses have been carried out for two different motor scales: the lab scale geometries used are related to both a test campaign conducted by Grosse in 2009, and a test campaign conducted at CISAS by Bettella in 2011; the increased scale geometry has instead been taken from CISAS 2011 tests.

At increased scale (three times the thrust of lab scale), the reference combustion efficiency was 80%, and it was raised at 94% with the addition of a diaphragm. Combustion stability was enhanced as well. Another advantage of the diaphragm related to post-combustion chambers and aft-end mixers is to enhance regression rate downstream of it. At lab scale and with the smaller diaphragm, regression rate was increased up to +90% (4.5 mm/s) compared to literature data referring to a no-diaphragm configuration. At increased scale, the increase was of +65 % (4.2 mm/s). Further research is needed, but these experiments showed that diaphragms can be used to design compact and efficient single-port and paraffin-based hybrid rocket motors.

Another study has been performed about vortex injection in hybrid rockets; in this case the path followed is twofold: first of all, the flow field has been simulated with a CFD code, then fire tests have been performed on a lab-scale rocket.

It has been shown by the experiments conducted that vortex injection lowers the chamber pressure oscillations compared to the corresponding axial injection case from more than 7% down to 4%. Moreover, regression rate has been increased by 41%, and the *a* coefficient of its law has been raised by 67%compared to the corresponding axial value. This last value, indeed, shows a constant behaviour throttling down the oxidizer mass flow. The increase is due to the higher wall heat flux at the grain surface, given by the higher velocity and thermal gradient of the fluid. Combustion efficiency has been increased with vortex injection due to the higher turbulence flow that enhances the mixing of the reactants. The axial case showed a combustion efficiency of 76% , while for the vortex case this parameter was increased up to 90%.

The CFD analysis had the purpose of both helping during the design phase and understanding vortex physics coupled with the combustion process. The study carried out first of all analyses the difference between axial and vortex injection: a higher wall heat flux (given by the higher thermal gradient and fluid velocity of the flow at the grain surface) allows a higher regression rate, and the higher turbulence enhances the mixing of the reactants, increasing in turn combustion efficiency. Analytical considerations showed a forced vortex inside the combustion chamber, and a pressure gradient as a result. It has been found that the combustion process tends to straighten the fluid lines reducing the swirl angle, due to an increase of velocity in the axial direction.

The results of vortex injection in terms of efficiency are illustrated in this work and compared to the corresponding experimental tests; a comparison with axial injection tests is also presented and discussed.

The combustion chamber design has been improved to enhance once again combustion efficiency: in fact, for example the use of a mixer enables an increase in combustion efficiency, which is often underestimated by the CFD, but that can be well observed by the results of the experimental tests. The simultaneous improvement of the injection process and the introduction of a mixing device (a diaphragm-like device inside combustion chamber) can produce a combustion efficiency increase up to 96%.