Acta Astronautica 128 (2016) 257–261

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/aa

Integrated approach for hybrid rocket technology development

Francesco Barato*, Nicolas Bellomo, Daniele Pavarin

Department of Industrial Engineering, University of Padua, Via Venezia 59/4, 35131 Padova, Italy

ARTICLE INFO

Article history:
Received 12 April 2016
Accepted 14 July 2016
Available online 16 July 2016

Keywords:
Hybrid rocket motor
Integrated approach
System design
Optimization

ABSTRACT

Hybrid rocket motors tend generally to be simple from a mechanical point of view but difficult to optimize because of their complex and still not well understood cross-coupled physics. This paper addresses the previous issue presenting the integrated approach established at University of Padua to develop hybrid rocket based systems. The methodology tightly combines together system analysis and design, numerical modeling from elementary to sophisticated CFD, and experimental testing done with incremental philosophy. As an example of the approach, the paper presents the experience done in the successful development of a hybrid rocket booster designed for rocket assisted take off operations. It is thought that following the proposed approach and selecting carefully the most promising applications it is possible to finally exploit the major advantages of hybrid rocket motors as safety, simplicity, low cost and reliability.

1. Introduction

1.1. *Are hybrids simple?*

A hybrid rocket is a rocket that stores its propellants in two different and separated phases, one solid and the other either gas, or liquid. In a classical hybrid rocket motor, the liquid oxidizer is injected at the head-end of the combustion chamber where it is vaporized and then reacted with the vaporized solid fuel. Combustion occurs in a boundary layer diffusion flame adjacent to the surface of the solid fuel (Figs. 1 and 2).

Hybrid rocket motors have gained much interest in recent times for their perceived advantages such as simplicity, reliability, safety and low cost. These claimed advantages are blatantly obvious to anybody working with hybrid rockets for simple applications like for example lab-scale testing or sounding rockets. However, hybrid rockets have never been able to exploit their peculiar features on more performing applications. One of the reasons is related to the fact that the mechanical simplicity of hybrid rockets conceals a complex physic. In some aspects, hybrids are more complex to understand and consequently to optimize than both liquids and solids. Compared to liquids, the fuel mass flow cannot be directly controlled. Compared to solids, hybrid regression rate is not a relatively simple function of pressure that can be determined in small scale burning tests. Even if apparently hybrid regression rate is a simple function of the oxidizer mass flux, the data obtained by a series of small scale tests can be totally misleading when applied to a different scale or configuration. Hybrid fuel production has a complex and not well known dependency on many physical and chemical parameters as well on the internal fluid dynamic in the combustion chamber. Hybrid regression rate changes both with time and space. Hybrid fuel production depends both on the fuel surface and the port area (through the oxidizer mass flux). This double geometrical constraint makes much more difficult than with solids to find an optimized shape for a specific thrust profile and case L/D considering also that the O/F ratio is not an intrinsic property of the casted propellant (unless high performances are not necessary, in this case in principle throttling can satisfy any thrust profile). It is important to remind that due to the mass flux dependency the hybrid thrust profile is always much more regressive than the behavior of its burning area. For a constant oxidizer flow a neutral or regressive grain will always produce a strong regressive behavior with an O/F shift toward higher values. With a progressive grain the thrust could be regressive, neutral or regressive depending on the situation, with also the O/F ratio that could vary in any direction.

Hybrid rocket combustion is strongly coupled. In fact, in a conventional hybrid motor, thrust and O/F ratio cannot be controlled independently. O/F ratio and residuals are also related [2], as a change in the burning surface affects the fuel production (so try to burn the fuel residuals at constant oxidizer flow will produce a strong O/F shift toward higher values). The O/F ratio changes with

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* Corresponding author.
E-mail addresses: francesco.barato@unipd.it (F. Barato), nicolas.bellomo@unipd.it (N. Bellomo), daniele.pavarin@unipd.it (D. Pavarin).

http://dx.doi.org/10.1016/j.actaastro.2016.07.023
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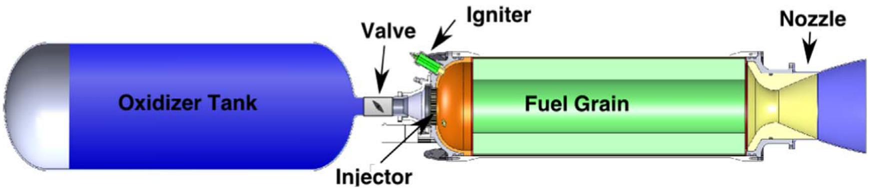

Fig. 1. Classical Hybrid Rocket Motor Scheme (courtesy of SPG [1]).

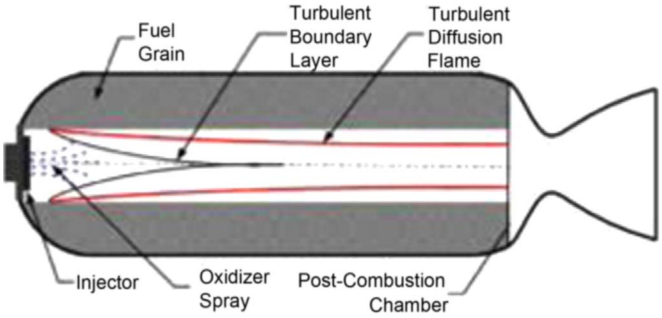

Fig. 2. Classical Hybrid Rocket Boundary Layer Combustion (courtesy of SPG [1]).

time, throttling and position in the combustion chamber. Several O/F ratios can be defined: the global O/F ratio of the chamber, the global O/F ratio up to the coordinate x, the flame O/F ratio etc.

The hybrid is characterized by a typical stratified diffusive flame that rises from the surface to the axis along the port [3]. Its fluid domain has large gradients of temperature, velocity, and chemical species in both the longitudinal and normal direction. In a hybrid, the energy is not released in a specific zone as in liquids or near the propellant surface as in solids, but it is distributed along the port at different axial and radial positions. This aspect makes the modeling of hybrid combustion a challenging task. In solid rockets, the flame is located near the surface and the chamber gas dynamic can be simplified as the near isentropic flow of the product gases. In a hybrid, the flame is located inside the fluidflow and produces a strong distortion of the reference non-reacting flow.

One of the peculiar characteristic of hybrids is the lack of an explicit relation between the energy release and the pressure as in solids and liquids, complicating the understanding of hybrids' instabilities [4]. In both liquid and solid systems, pressure-coupled instabilities have been known to lead to catastrophic failures. This type of failure has thus far not been experienced in hybrid systems [5]. However, even if benign, instabilities can prevent a propulsion system to reach operational status. Hybrid rockets can experience several type of instabilities. Some of them are similar to those found in solids and/or liquids like acoustics or feed-coupled ones [6–8]. Others are specific to hybrid rocket propulsion [9–11] (and the analog solid ramjet) and related to its peculiar boundary layer combustion [12–14]. In particular, proper flame holding of the hybrid diffusion flame has been recognized as critical for hybrid motor stability [15–18]. Generally, flame holding is accomplished through increasing residence time and heating of the oxidizer in the pre-chamber [19,20] (through passive means like recirculation zones [21,22] or active ones like heat sources [23]). Unfortunately, a comprehensive understanding of hybrid rockets instabilities and mitigation practices is still lacking.

As outlined earlier, the hybrid fuel regression rate is still not well understood and has very complex dependencies on many parameters. Moreover, reliable scaling rules for regression rate, motor stability and efficiency are still to be found.

It is therefore difficult to design a hybrid propulsion system without being constrained on the configuration, scale and propellant combination from which the experimental data have been obtained.

Finally another possible feature of hybrids can be the use of a self-pressurized oxidizer. Self-pressurization can be applied also to liquids but up to now has been used mainly on hybrids because of their frequent focus on simplicity. However, as with hybrids in general, self-pressurization, again, shifts the complexity from the mechanical point of view to the physical behavior. The behavior of the two phase flow in the tank and the injector during the discharge is much more difficult to predict and model than a classical incompressible fluid as in the feed systems of most liquid engines. Self-pressurization makes the mass flow and consequently motor behavior strongly sensitive to the ambient conditions and to stratification inside the tank [24].

To solve all the issues of hybrid propulsion too often complex path are taken that compromise the original simplicity of the hybrid design, deteriorating its inherent advantages [25]. Typical examples are the addition of an oxidizer to the fuel grain in order to increase the regression rate, the addition of a feedline that inject part of the oxidizer in the postchamber in order to compensate the O/F shift, the injection of a pyrophoric liquid to help motor stabilization, the use of multiport grain to shorten the chamber L/D. Usually this kind of solution jeopardize the inherent benefits of hybrid rocket propulsion so they end up to be only a technical risky alternative than current mature and demonstrated technologies.

2. Approach to hybrid rocket development

2.1. Integrated approach

Considering the aforementioned issues the use of an integrated approach is particularly necessary for the success of a hybrid-based program. Here integrated approach means the philosophy to couple together in a synergistic way different methodologies and tools to get an understanding of what is going on and drive the engineer's choices. An integrated approach is fundamental both in the system design phase as during motor development. In the design phase the complex behavior of hybrids has a considerable impact on the system design. The role of the O/F ratio and the coupling between it, the thrust and residuals requires generally at least a basic numerical model (except for very simple cases).

The volume loading of the combustion chamber is constrained by the regression rate of the fuel and the selected geometry. Moreover, the impact of the chamber volume loading on the whole system is determined by the global O/F ratio. The external shape of the combustion chamber (i.e. its L/D) cannot be arbitrarily chosen without incurring in significant penalties/issues.

With conventional rockets, as a first approximation, the system engineer can deal with the propulsion system as a black box and set some specific requirements (size, total impulse, thrust, burning time…) that are suitable for its design. However, much more than with solids and liquids, the capability of hybrid to achieve high performances is very sensitive to the choice of the aforementioned motor parameters. While an integrated approach is favorable in any case, it is essentially fundamental in the case of hybrid rockets. The system and the rocket have to be matched in order to synergistically strengthen each other. It could easily happen that the perfect