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Parametric study and performance analysis of hybrid rocket motors with double-tube configuration

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ABSTRACT

The practical implementation of hybrid rocket motors has historically been hampered by the slow regression rate of the solid fuel. In recent years, the research on advanced injector designs has achieved notable results in the enhancement of the regression rate and combustion efficiency of hybrid rockets. Following this path, this work studies a new configuration called double-tube characterized by injecting the gaseous oxidizer through a head end injector and an inner tube with injector holes distributed along the motor longitudinal axis. This design has demonstrated a significant potential for improving the performance of hybrid rockets by means of a better mixing of the species achieved through a customized injection of the oxidizer. Indeed, the CFD analysis of the double-tube configuration has revealed that this design may increase the regression rate over 50% with respect to the same motor with a conventional axial showerhead injector. However, in order to fully exploit the advantages of the double-tube concept, it is necessary to acquire a deeper understanding of the influence of the different design parameters in the overall performance. In this way, a parametric study is carried out taking into account the variation of the oxidizer mass flux rate, the ratio of oxidizer mass flow rate injected through the inner tube to the total oxidizer mass flow rate, and injection angle. The data for the analysis have been gathered from a large series of three-dimensional numerical simulations that considered the changes in the design parameters. The propellant combination adopted consists of gaseous oxygen as oxidizer and high-density polyethylene as solid fuel. Furthermore, the numerical model comprises Navier-Stokes equations, k-ε turbulence model, eddy-dissipation combustion model and solid-fuel pyrolysis, which is computed through user-defined functions. This numerical model was previously validated by analyzing the computational and experimental results obtained for conventional hybrid rocket designs. In addition, a performance analysis is conducted in order to evaluate the influence in the performance provoked by the possible growth of the diameter of the inner fuel grain holes during the motor operation. The latter phenomenon is known as burn through holes. Finally, after a statistical analysis of the data, a regression rate expression as a function of the design parameters is obtained.

1. Introduction

The increase of the low regression rate of solid fuel is one of the main challenges that classical Hybrid Rocket Motors (HRM) need to face in order to widespread their applicability. Indeed, the performance offered by HRM is better than that of Solid Rocket Motors (SRM) and comes at lower cost if compared to Liquid Rocket Engines. However, it is necessary to enhance the regression rate, which is constrained by the diffusion-limited combustion process that takes place at the turbulent flame boundary layer. In recent years, the research on advanced injector designs has achieved notable results in the enhancement of the regression rate and combustion efficiency of hybrid rockets. Precisely, the fluid dynamics inside the combustion chamber can be noticeably altered thanks to the injection of the oxidizer in a non-classical way, such as using swirl-injection [1,2] or vortex configuration [3]. Following this path, this work presents the characterization of a new kind of injector configuration called double-tube. The main feature of this design consists of the injection of the gaseous oxidizer through a head end injector and an inner tube with injector holes distributed along the motor longitudinal axis (see Fig. 1). The inner fuel grain, which is supported by the inner tube, allows the oxidizer jets to enter the combustion chamber at a given injection angle. In this way, the injection of the oxidizer through the inner tube allows to achieve a higher control of the O/F along the combustion chamber thanks to a

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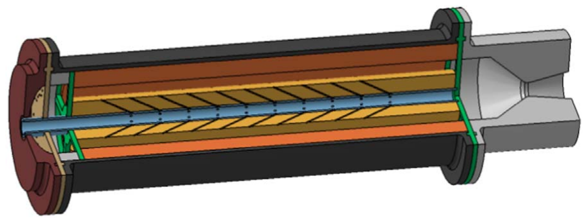

Fig. 1. Double-Tube Hybrid Rocket Motor concept.

customized oxidizer distribution. Moreover, the injection of the oxidizer counter-flow results in an increased residence time and a better mixing of species.

In order to define the design parameters of the double-tube, it is necessary to consider the number of inner tube injector holes, their distribution and diameter d_{IT}, the number of head end injector holes, their distribution and diameter d_{HE}, the injection angle α and the parameter λ. The injection angle α is the angle between the motor's longitudinal axis and the axis of the inner tube holes defined positive counterclockwise. Furthermore, the parameter λ is the ratio that relates the oxidizer mass flow rate injected through the inner tube $\dot{m}_{OX\,IT}$ with respect to the total oxidizer mass flux $\dot{m}_{OX}$ as:

$$\lambda = \frac{\dot{m}_{OX\,IT}}{\dot{m}_{OX}} \tag{1}$$

Consequently, if $\lambda = 0$ denotes that all the oxidizer is injected from the head end injector, $\lambda = 1$ represents that all the oxidizer is injected from the inner tube injector holes.

The double-tube design has been numerically simulated [4] and experimentally tested [5]. In both cases, the configuration has demonstrated a significant potential for improving the performance of hybrid rockets. For example, the CFD analysis of the double-tube configuration has revealed that this design may increase the regression rate over 50% with respect to the same motor with a conventional axial showerhead injector[4]. In case of the experimental tests firings, they proved that the double-tube design is capable of achieving a regression rate over twice larger than a conventional axial showerhead injector[5]. For both cases, although the initial design was not optimized, the results were very promising. Thereby, in order to fully exploit the advantages of the double-tube concept and optimize its design, it is necessary to acquire a deeper understanding of the influence of the different design parameters in the overall performance. To do so, a parametric study is carried out taking into account the variation of the oxidizer mass flux rate, the ratio of oxidizer mass flow rate injected through the inner tube to the total oxidizer mass flow rate, and injection angle. Since the preparation of experimental tests firings is lengthy and expensive, the data for the analysis have been gathered from a large series of three-dimensional numerical simulations that considered the changes in the design parameters. In these simulations, high-density polyethylene (HDPE) is adopted as solid fuel and gaseous oxygen as oxidizer. Furthermore, the paper evaluates the influence on the performance provoked by the burn-through holes. Note that burn-through holes appear due to the growth of the diameter of the inner fuel grain holes during the motor operation.

The paper is organized as follows. The first section introduces the concept of double-tube HRM as well as its state-of-the-art. The second section describes the numerical model used to generate the data to later present the numerical results in the third section and address the parametric study in the fourth one. Finally, the fifth section evaluates the effects in performance due to the burn-through holes, and in section six the main conclusions of the work are drawn.

2. Numerical model

2.1. Fluid dynamics governing equations

The gas phase governing equations used in the three-dimensional numerical simulation include the standard Navier-Stokes equations, species transport and turbulence. Moreover, the numerical simulation was validated for conventional hybrid rocket designs by comparing the simulation results against experimental tests data [1–8]. In this way, the coupled equations can be expressed in a uniform vector form as:

$$\frac{\partial \vec{Q}}{\partial t} + \frac{\partial \vec{E}}{\partial x_i} = \frac{\partial \vec{V}}{\partial x_i} + \vec{H} \tag{2}$$

where the vectors $\vec{Q}$, $\vec{E}$, $\vec{V}$ are respectively:

$$\vec{Q} = \begin{bmatrix} \rho \\ \rho u_i \\ e \\ \rho k \\ \rho \varepsilon \\ \rho Y_m \end{bmatrix};\quad \vec{E} = \begin{bmatrix} \rho u_i \\ (\rho u_i u_j + P_t)\delta_{ij} \\ (e + P_t)u_i \\ \rho u_i k \\ \rho u_i \varepsilon \\ \rho u_i Y_m \end{bmatrix};\quad \vec{V} = \begin{bmatrix} 0 \\ \tau_{ij} \\ u_j \tau_{ij} + \lambda' \frac{\partial T}{\partial x_i} \\ \mu_k \frac{\partial k}{\partial x_i} \\ \mu_\varepsilon \frac{\partial \varepsilon}{\partial x_i} \\ \rho D_m \frac{\partial Y_m}{\partial x_i} \end{bmatrix}$$

In these expressions, the subscript m indicates the number of chemical species, being $m = 1, 2, \ldots, N - 1.N$ is the total number of chemical species, $i = 1, 2, 3$ and $j = 1, 2, 3$. In addition, Y_m represents the mass fraction of the m-th species and P_t is the effective pressure. Note that P_t is given by the sum of the static pressure P and pressure due to fluctuation velocity $2/3\rho k$. Finally, the vector $\vec{H}$ contains the source terms related to turbulence, combustion and solid fuel pyrolysis. Thereby, this term is related with the user defined functions used during the simulation.

The turbulence model implemented for this simulation model is the realizable $k - \varepsilon$ model with enhanced wall treatment. This turbulence model is appropriate for simulating the channel and boundary layer flows [9,10]. Based on Boussinesq hypothesis, the transport equations for the kinetics energy and turbulent dissipation rate are given as follows:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon \tag{3}$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \rho C_1 S\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b \tag{4}$$

where

$$C_1 = \max\left[0.43, \frac{\eta}{\eta + 5}\right], \quad \eta = S\frac{k}{\varepsilon}, \quad S = \sqrt{2S_{ij}S_{ij}}$$

In these equations, G_k represents the generation of turbulence kinetic energy, G_b is the generation of turbulence duo to buoyangcy. Y_M represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate. $C_2 = 1.9$ and $C_{1\varepsilon} = 1.44$ are constant. $\sigma_k = 1.0$ and $\sigma_\varepsilon = 1.2$ are the turbulent Prandtl numbers for k and ε.

2.2. Combustion model and solid fuel pyrolysis

The combustion model used assumes that the high-density polyethylene (HDPE) is supposed to be C_2H_4. The rate of pyrolysis, which is also known as the regression rate of solid fuel, is described by a semi-empirical formulation in the form of an Arrhenius law:

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