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Combustion characteristics of hybrid rocket motor with segmented grain

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ABSTRACT

In this paper, to improve the combustion efficiency and the regression rate in hybrid rocket motor, we introduce a concept that two different grain configurations are deployed into one combustion chamber, which is called the segmented grain in following chapters. Both numerical and experimental investigations are conducted. In the simulation part, the combustion efficiency and the distributions of regression rate, temperature and mass fraction of species in segmented grain cases are obtained. The corresponding firing tests are performed by the lab-scale motor with 90% H_2O_2 and PE propellant combination. The combustion efficiency and average regression rates are achieved in each test case. The numerical and experimental results agree well, and demonstrate that the segmented grain configuration proves its ability of enhancing the combustions efficiency and the regression rate of the hybrid rocket motor. Comparing with the contrast cases, the combustion efficiency of segmented grain cases are raised by 15% and around 10% in the simulations and tests, respectively. The regression rates of the after-section grain are also increased according to simulation and test results.

1. Introduction

A hybrid rocket in general uses solid propellant as the fuel and liquid propellant as the oxidizer. In recent years, the studies as to hybrid rocket motor have been focused by an increasing number of researchers, for its merits such as safety, low cost, less pollution and reliability. However, hybrid rocket motors suffer several problems. One remarkable drawback is low combustion efficiency, while the other one is low regression rate. The first flaw is mainly attributed to the incomplete mixing of the core oxidizer flow and the vaporized fuel over the grain surface. The second one can be considered as a consequence of diffuse combustion in the boundary layer, which limits heat transfer to the fuel wall.

Many efforts have been made to deal with the two problems. The hybrid rocket motor using a swirl oxidizer injector, which can extend the resident time of the oxidizer and enhance the heat exchange, increases both combustion efficiency and regression rate [1]. Diaphragms settled in solid grain provide another method to improve combustion efficiency. Dr. Grosse et al. studied the use of diaphragm in a lab-scale motor. Their research demonstrated that the diaphragms positioned between 24–33% of the grain length achieved very high combustion efficiencies and very high and smooth regression rates in the second grain section [2]. In addition, the performance of the hybrid rocket motor can be promoted by reforming internal grain configuration. A helical grain configuration cooperating with swirl injection is an effective way to enhance regression rate by minimizing the disadvantage of swirl injector and overcoming the negative effects by using other applicable options [3]. Furthermore, grain configurations such as concave-convex surface grain have been experimentally investigated. Using the concave-convex grains increased the overall regression rates up to about 1.7–2.0 times in comparison with those of the cylindrical grains at the same oxidizer mass flux [4].

To take a further step, we conceive an idea that applying the segmented grain to improve combustion efficiency and regression rate. The segmented grain is supposed to be a combination of two separated grains, and each section adopts different types of internal grain configuration. The combinations of cylindrical single port grain in fore-section and three ports grain in after-section are studied in this article. Moreover, a mid-chamber is set between the two sections to enhance the mixing of the oxidizer and the fuel generated before it.

In this paper, numerical simulations followed with an experimental campaign have been performed. Six different combinations of fore-section (single port) and after-section (three ports) grain length have been set up as experimental group. While,

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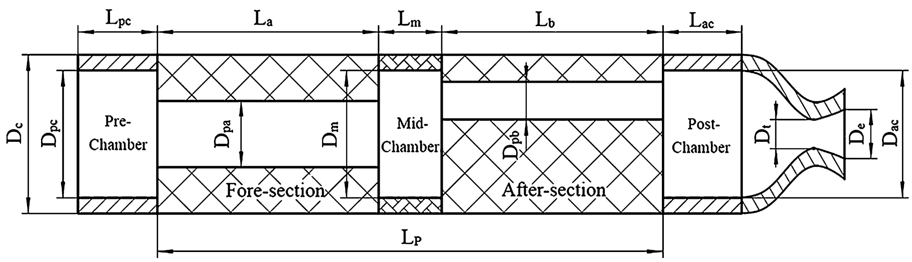

Fig. 1. Cutaway sketch of lab-scale motor.

Table 1
Main parameters of the lab-scale motor.

Name	Value (mm)
Combustion chamber inner diameter D_c	100
Pre-chamber inner diameter D_{pc}	80
Mid-chamber inner diameter D_m	80
Post-chamber inner diameter D_{ac}	80
Nozzle throat diameter D_t	18
Nozzle exit diameter D_e	31.18
Single port grain inner diameter D_{pa}	42
Three ports grain inner diameter D_{pb}	24
Pre-chamber length L_{pc}	30
Mid-chamber length L_m	30
Post-chamber length L_{ac}	40
Total grain length L_p	375

two subjects, each of which shares the same grain configuration in both fore-section and after-section, are presented as control group. The main object of numerical simulations is to establish 3D numerical models and obtain the combustion efficiency, the three-dimensional distribution characteristics of fuel regression rate, temperature and mass fraction of species distribution in segmented grain hybrid rocket motors. The corresponding experimental tests are conducted for further research of segmented grain effects. The laboratory-scale hybrid rocket motor with 90% hydrogen peroxide (HP) and polyethylene (PE) propellant combination is used in this experiment. This paper focuses on whether the segmented grain configuration can enhance the combustion efficiency and regression rate. Both simulation and experiment results reveal that the segmented grain could be a helpful method to improve the combustion efficiency and the average regression rate.

2. Numerical simulations

2.1. Geometry model

Fig. 1 shows the cutaway view sketch of the laboratory scale motor used in this paper. The motor applies catalyst bed to ignite and continually provide catalyzed hydrogen peroxide. The fuel grain is divided in two sections. The fore-section adopts single port grain, and 3 ports grain is placed in after-section, and the diameters of all grain ports are designed to satisfy the condition that the total cross-sectional area of grain port(s) maintains around the same constant. Accordingly, the main parameters of the motor are demonstrated in Table 1.

As shown in Fig. 1, L_a represents the fore-section grain length, and L_b stands for after-section grain length. The sum of fore-section grain length L_a, after-section grain length L_b and Mid-chamber length L_m is locked at 375 mm. With the value of L_a and L_b changing, we create 6 experimental cases (T1–T6) and 2 contrast cases (S1, S2) which hold the same grain configuration in both fore-section and after-section. Details of each test case are illustrated in Table 2.

Table 2
Specifications of test cases.

Case name	L_a (mm)	L_b (mm)	Fore-section configuration	After-section configuration
T1	145	200	Single port	Three ports
T2	175	170	Single port	Three ports
T3	205	140	Single port	Three ports
T4	235	110	Single port	Three ports
T5	265	80	Single port	Three ports
T6	295	50	Single port	Three ports
S1	205	140	Single port	Single port
S2	205	140	Three ports	Three ports

For a three-dimensional CFD case, the structured hexahedral mesh has the advantages of good orthogonality and grid quality [5]. Thus, we build a structured mesh for this one. Due to the symmetry characteristic of the flow field, only one-sixth of it is selected as the computational domain to reduce mesh quantity and save computer sources. The meshes are clustered near the fuel surfaces and walls to meet the requirement of the turbulence model for the numerical simulation.

Fig. 2 demonstrates the mesh of the whole computational domain in case T3. It contains 481 thousand hexahedral cells and 512 thousand nodes. The oxidizer inlet, mid chamber and post-chamber meshes are shown in Fig. 3, Fig. 4 and Fig. 5, respectively.

2.2. Numerical models

Three-dimensional numerical models are established with fluid dynamics, turbulence, solid fuel pyrolysis and gas phase combustions. The propellant combination in this paper is 90% HP oxidizer and PE fuel. For the application of catalyst bed, we can reckon the oxidizer has decomposed to gaseous oxygen and water vapor before spraying into pre-chamber. Thus, only gas phase is considered for simplifying physical processes. The simulations are performed by ANSYS Fluent and User defined functions (UDFs). The main process and iteration are executed by Fluent solvers, while the solid-gas coupling and fuel pyrolysis are conducted in UDFs. The numerical models are described as follows.

2.2.1. Governing equations

The gas-phase governing equations in simulations couple the three-dimensional Navier–Stokes equations with continuity equation, energy conservation equation and species transport equations.

2.2.2. Turbulence model

Realizable k–ε turbulence model is adopted in this case. This turbulence model exhibits superior performance for flows involving rotation, boundary layers under strong adverse pressure gradients, separation and recirculation. In comparison with other measures, Realizable k–ε demonstrates a superior ability to capture the mean flow of the complex structures [6].

Enhance wall treatment is selected as near-wall treatment, which requires the y^+ value at the first node adjacent to the wall should be around 1.

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