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Unsteady simulation and experimental study of hydrogen peroxide throttleable catalyst hybrid rocket motor

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ABSTRACT

In this paper, a series of simulations and experiments about hydrogen peroxide throttleable catalyst hybrid rocket motor were conducted during thrust regulation process. Some characteristics of this motor were investigated such as regression rate, pressure in chamber and thrust. The motor used polyethylene (PE) as the solid fuel and 90% hydrogen peroxide (H_2O_2) as the oxidizer. To investigate transient process of this throttleable motor, an unsteady simulation model was developed. The realizable k–ε turbulence model combined with the Eddy-Dissipation combustion model was applied in this paper, and gas–solid coupling model was used to simulate the regression process on the solid fuel surface. The distributions of temperature, pressure and solid fuel regression rate were obtained. A series of tests were conducted to verify the accuracy of the simulation model. From the comparison of the pressure in chamber between the simulation and test, the maximum error is 9%. The numerical model could predict the characteristics of this motor. The simulation results and the experimental data indicate that the chamber pressure and fuel regression rate cannot response to the oxidizer mass flow rate change immediately, it requires a lag time to readjust to new equilibrium.

1. Introduction

As the main power source of the space transportation and aerospace vehicles, the thrust of rocket motor is a significant factor on the capability of spacecrafts [1,2]. The throttleable rocket motor has advantages on space transportation and space flight missions because of its controllable thrust. For manned space flight, with a throttleable motor the load which the astronauts suffered would be controlled [3]. For soft landing on the surface of the planet such as Apollo and Chang'E Mission, the throttleable motor is the only available manner [4–6]. For rendezvous and docking, the throttleable motor could reduce the amount of attitude control engines to simplify the power system, also it could combine the function of the attitude control engine and rail control engine due to the variable thrust [7,8]. For missiles, it could improve the maneuverability [9,10].

Currently, spacecrafts and missiles usually use the liquid rocket and solid rocket as their propulsion system. It is realizable to obtain variable thrust for these two kinds of rockets. For liquid rocket, it need to adjust both oxygen and fuel synchronously to maintain the oxygen-to-fuel ratio stable to keep the performance of motor while changing the thrust. For solid rocket, it need to redesign the configuration of the grain which is costly and complex and the thrust changing program depends on the setting before launching. A typical hybrid rocket motor using liquid oxidizer and solid fuel which is the emphasis of this paper, offers a number of advantages over liquid rocket and solid rocket in the areas of safety, throttling, environmental cleanliness, low cost and so on. Compared with liquid rocket, hybrid rocket motor can be throttled easily by changing the oxidizer mass flow rate. Compared with solid rocket, hybrid rocket motor has advantages in the areas of restart and real-time control [11–13]. So hybrid rocket motor is very suitable as the throttleable rocket motor [14–16]. In 2010, B.L. Austin Jr., et al. conducted a series of throttleable hybrid rocket tests in Purdue University. In these tests the efficiency of the motor changed from 91%∼100% while the thrust varying from 44.5 N to 445 N [17].

Typically the liquid oxidizer will been decomposed to gas when get into the chamber, then the gas oxidizer will flow over the solid fuel, transfer heat to the solid fuel. Then the solid fuel will pyrolysis to gas fuel. The gas oxidizer and fuel will react close to the solid fuel surface and form a turbulent, reactive boundary layer. The combustion in hybrid rocket chamber is a typical diffusion com-

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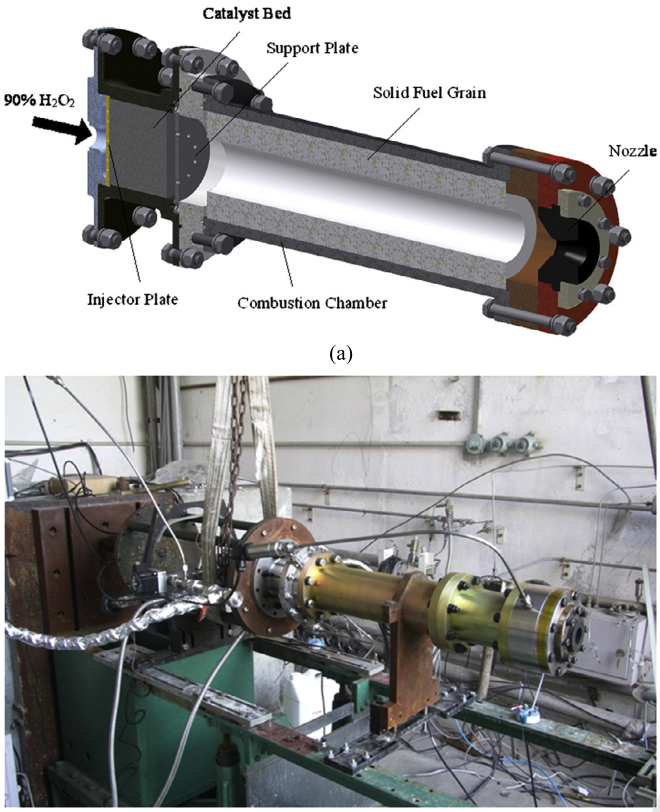

(a)

(b)

Fig. 1. H_2O_2/PE throttleable catalyst hybrid rocket motor.

bustion, the regression rate which represents the pyrolysis rate of solid fuel is the key aspect for hybrid rocket motor efficiency evaluation. It depends on thermal energy flux spent for gasification, and gasification conditions [18].

Lots of numerical simulation studies of working process about hybrid rocket motor have been conducted. Most of these focus on steady combustion and the flow in chamber with the assumption that solid fuel interior is steady and the fuel flow rate is obtained from steady energy conservation equations and empirical formula [19]. However, there are few reports about numerical simulation on variable thrust hybrid rocket motors [20]. In transient processes of thrust regulation of variable thrust hybrid rocket motors, the engine inner flow, the solid fuel inner temperature and the regression rate of solid fuel cannot be steady immediately. Thus an unsteady numerical simulation must be conducted to reflect flow field structure in transient process. Test is a significant means to study hybrid rocket motors. Regression rate, combustion performance, dynamic performance and so forth obtained from tests which are data bases for study on theory and numerical simulation of hybrid rocket motors can perfect and improve engine theory and numerical simulation. Therefore, some steady tests and thrust regulation tests are conducted.

2. Experimental facilities

A H_2O_2/PE throttleable catalyst hybrid rocket motor system is established which includes H_2O_2/PE throttleable catalyst hybrid rocket motor, oxidizer feed system, measurement and control system, test bed and image monitoring system

This motor uses 90% H_2O_2 and PE as propellant. As shown in Fig. 1, this motor consists of catalyst bed, combustion chamber, PE fuel and nozzle. The catalyst bed is the same as Ref. [21] and the catalyst bed load is 2∼15 g/cm^2 · s. The inner diameter of the combustion chamber is 100 mm. To strengthen the mix of combustion products, the pre-combustion chamber and post-combustion chamber are designed. The solid fuel grain is the single-hole type whose inner diameter is 35 mm. The outer diameter of the solid fuel grain is 100 mm and the length-diameter-ratio is 15. The nozzle is a sink conical nozzle whose throat insert is copper infiltrated tungsten. The major parameters of the motor are listed in Table 1.

Table 1
Parameters of the test motor.

Parameters	Motor A
Mass flow rate of H_2O_2 $\dot{m}_{H_2O_2}/(\mathrm{kg/s})$	0.1∼0.5
Inner diameter of the fuel D_{in}/mm	35
Length of the fuel L/mm	525
Diameter of the throat D_t/mm	18

The oxidizer feed system is a extrusion type conveying system, including gas rationing system, tank of liquid H_2O_2, variable area cavitating venturi, master valve and N_2 inlet blowdown and so on, as Fig. 2 shows. The oxidizer mass flow rate could be controlled by the variable area cavitating venture [22] as Fig. 3 shows. The pintle in the valve can change the throat area of the venturi by a forward and backward movement which is called the stoke. Based on Ref. [22], the mass flow changes linearly with the stoke of the pintle. For instance, there is a coriolis flow meter produced by emerson® in the feed system to measure the oxidizer mass flow rate. The range of the coriolis flow meter is 2270 g/s with 0.1% precision.

The motor is placed on the device of thrust measurement, which is the same as the Ref. [23]. Is set to get the pressure of the chamber from the aft-chamber. The range of the pressure sensor is 10 MPa with 0.25% precision. Is set to get the thrust of the motor in front of the motor, the range of the thrust sensor is 3000 N with 0.1% precision.

To get the laws of the regression rate of the 90% H_2O_2/PE hybrid rocket motor, 5 stable tests were conducted. The data of these tests and the parameters of the motor are listed in Table 2. And 5 thrust regulation tests were conducted, the parameters of the motor are shown in Fig. 4.

3. Simulation model and conditions

3.1. Simulation model description

3.1.1. Fluid dynamics governing equations

The governing equations of gas phase were described with finite volume method and the coupled solution algorithm was employed to solve the discredited equations.

$$\frac{\partial \rho \Phi}{\partial t}+\frac{\partial}{\partial x}(\rho u \Phi)+\frac{1}{r}\frac{\partial(r\rho v\Phi)}{\partial r} = \frac{\partial}{\partial x}\left(\Gamma\frac{\partial \Phi}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\Gamma\frac{\partial \Phi}{\partial r}\right)+S_\Phi \tag{1}$$

where Φ is generic variable representing the axial velocity, radial velocity, temperature and mass fraction. Γ is the diffusion coefficient, S_Φ is the source term.

Inside the solid fuel, the conduction processes are governed by the following equation,

$$\frac{\partial T}{\partial t}=\frac{\lambda_s}{\rho_s c_s}\left(\frac{\partial^2 T}{\partial x^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial r^2}\right)+\frac{\dot{r}}{r}\frac{\partial(rT)}{\partial r} \tag{2}$$

where the first term on the right side of the equation represents the thermal diffusion in the solid fuel. The second term on the right side of the equation represents the heat dissipation caused by the extent of fuel boundary. λ_s is the conduction coefficient, ρ_s

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