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Effect of grain port length–diameter ratio on combustion performance in hybrid rocket motors

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ABSTRACT

The objectives of this study are to develop a more accurate regression rate considering the oxidizer mass flow and the fuel grain geometry configuration with numerical and experimental investigations in polyethylene (PE)/90% hydrogen peroxide (HP) hybrid rocket. Firstly, a 2-D axisymmetric CFD model with turbulence, chemistry reaction, solid–gas coupling is built to investigate the combustion chamber internal flow structure. Then a more accurate regression formula is proposed and the combustion efficiency changing with the length–diameter ratio is studied. A series experiments are conducted in various oxidizer mass flow to analyze combustion performance including the regression rate and combustion efficiency. The regression rates are measured by the fuel mass reducing and diameter changing. A new regression rate formula considering the fuel grain configuration is proposed in this paper. The combustion efficiency increases with the length–diameter ratio changing. To improve the performance of a hybrid rocket motor, the port length–diameter ratio is suggested 10–12 in the paper.

1. Introduction

Hybrid rocket motors (HRM) use liquid oxidizer and solid fuel as propellants. They have advantages such as safety, low cost, throttling and multiple restart capabilities. The HRM burns as a macroscopic turbulent diffusion flame where the oxidizer-to-fuel ratio (*O*/*F*) varies down the length of the chamber, ending at a composition that determines the motor performance [1]. And over the past decade, the HRM has been widely investigated by experiment study, theoretical analysis and numerical simulation. Kanazaki et al. proposed the conceptual design of single-stage rocket using hybrid rocket motor [2].

The fuel regression rate is a critical parameter that has the first order effects on the motor design and thereby the performance of the motor. Li et al. researched the regression rate distribution characteristics in hybrid rocket motors with numerical analysis [3]. The grain port diameter is an important parameter in the regression rate besides oxidizer mass flow. Studies have shown the average regression rate decreases with the increase of port diameter [4–6]. Rajiv Kumar studied that the use of protrusion improved the regression and combustion efficiency [7]. The improvement of swirl on regression rate researched by Kumar is more effective for short grains [8]. Sun et al. invested the regression rate and combustion performance of aluminum metallized HTPB with numerical simulation [9]. Strand et al. experimented to develop hybrid fuels with higher regression rates and reduced dependence on grain geometry and maximize potential specific impulse using low-cost materials [10]. Whitehead did experiment to investigate the increase in regression rate from adding a solid oxidizer and a catalyst to a hybrid fuel grain [11]. Thermal characterizations of the paraffin wax/low density polyethylene blends as a solid fuel are researched by Kim to increase the regression rate [12]. Chidambaram investigated the effect of oxidizer (AP) mixed fuel grain (HTPB) on regression and performance in GOX hybrid rocket motors [13]. Sun characterizes the regression rate behavior of hybrid rocker motor combinations using different oxidizers and hydroxyl-terminated poly-butadiene [14]. Gariani developed a code for the numerical simulation of combustion processes in hybrid rockets and analyzed the influence of mass flux and chamber pressure on the combustion process [15]. Pei researched the influence of cavity geometry parameters, including L/D ratio, aft wall angle and offset ratio, on combustion performance. A solid-fuel scramjet combustor with cylindrical section and L/D=4, $\theta = 45^{\circ}$, $D_d/D_u = 1.25 - 1.5$ has the best performance [16].

Plenty of theoretical research, numerical model and experiment on the fuel regression rate were conducted in the past. However, few works focus on the regression rate changing with the length–diameter ratio which leads the specific impulse loss. In

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addition, experiments of PE/90% HP hybrid rocker motor are less reported. The main purpose of this paper is to investigate the combustion with the changing grain's length–diameter ratio and oxidizer flux in the PE/90% HP hybrid rockets. Series of numerical and experimental tests under various oxidizer mass flow are conducted in this paper. The fuel regression rate formulas are fitted with numerical and experimental results and compared with each other.

2. Numerical simulation

A 2-D axisymmetric CFD model with turbulence, chemistry reaction, solid–gas coupling is built to investigate the combustion performance changing with the fuel grain configuration.

2.1. Numerical model

2.1.1. Model hypotheses

The combustion in the hybrid rocket motor chamber is a very complicated processes including multiphase heterogeneous phase flow and combustion. A few hypotheses are made as follows:

1) First assumption is made that the mixture gas in the chamber is perfectly ideal.
2) The flow is assumed a quasi-steady process because the fuel regression rate is quite small compared to the fuel characteristic length.
3) The radiation heat transfer is ignored in the simulation model.
4) The solid fuel reaction only occurs near the surface and directly generates the pyrolysis gas.

2.1.2. Governing equations

The governing equations were discretized using a 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, Γ and S_Φ are the general variable which represent the axial velocity, radial velocity, energy and mass fraction, the generalized diffusion coefficient and the generalized source items respectively, ρ is the density, t is the time, x and r are the axial and radial coordinates, u and v are the axial and radial velocities.

2.1.3. Turbulence model

The realizable $k-\varepsilon$ turbulence model was used in this paper and the transport equations for the turbulence kinetic energy k and its rate of dissipation ε were given as follows.

$$\frac{\partial \rho k}{\partial t} + \frac{\partial}{\partial x}(\rho k u) + \frac{1}{r}\frac{\partial (r\rho v k)}{\partial r} = \frac{\partial}{\partial x}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x}\right] + \frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial r}\right] + G_k - \rho\varepsilon \tag{2}$$

$$\frac{\partial \rho \varepsilon}{\partial t} + \frac{\partial}{\partial x}(\rho u \varepsilon) + \frac{1}{r}\frac{\partial (r\rho v \varepsilon)}{\partial r} = \frac{\partial}{\partial x}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x}\right] + \frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial r}\right] - \rho C_1 \frac{\varepsilon^2}{k + \sqrt{\nu\varepsilon}} \tag{3}$$

where μ is the viscosity coefficient, μ_t is the turbulent viscosity coefficient, σ_k and σ_ε are turbulent Prandtl number for k and ε, G_k represents the generation of turbulence kinetic due to the mean velocity gradients and C_1 is a constant.

2.1.4. Reaction model

The composition of the fuel pyrolysis products is ethylene. The combustion mechanism of ethylene with hydrogen peroxide was approximated by a simplified two-step reaction model.

$$C_2H_4 + 2O_2 \rightarrow 2CO + 2H_2O \tag{4}$$

$$CO + 0.5O_2 \rightarrow CO_2 \tag{5}$$

The problem of condensed material surface burning in a flow of oxidizer has been researched by Smirnov et al. [17,18]. The gas phase chemical reacts in a diffusion flame within the hybrid rocket motor, and the reaction rates strongly depend on the turbulent diffusion of the oxidizer and the evaporated fuel. For this reason, the eddy dissipation model is applied to calculate the reaction rates.

2.1.5. Solid–gas coupling model

The coupling between the solid and gaseous phases is obtained through the balance of energy and mass on the solid fuel surface.

The energy conservation can be written as follows.

$$-\lambda_g\left(\frac{\partial T}{\partial r}\right)_g = -\lambda_s\left(\frac{\partial T}{\partial r}\right)_s + \rho_s \dot{r}\left(h_g - h_s\right) \tag{6}$$

where, λ_g is the thermal conductivity of the gas near the fuel surface, h_g is the enthalpy of the fuel pyrolysis products at the surface temperature, h_s is the enthalpy of the solid fuel at the surface temperature, r is the radial coordinates, T is the grain temperature, ρ_s is the density of the grain, $\dot{r}$ is the regression rate of the grain.

The mass conservation is determined by

$$\rho_g v = -\rho_s \dot{r} \tag{7}$$

where, ρ_g is the gas density near the fuel surface, v is the radial velocity of the gas near the fuel surface.

2.1.6. Fuel pyrolysis model

A semi-empirical formulation in the form of Arrhenius law is introduced to calculate PE regression rate.

$$\dot{r} = A \cdot e^{-\frac{E_a}{R_u T_s}} \tag{8}$$

Where activation energy E_a is 125.604 kJ/mol pre-exponential factor A is 2678.1 m/s. T_s is the surface temperature of the grain.

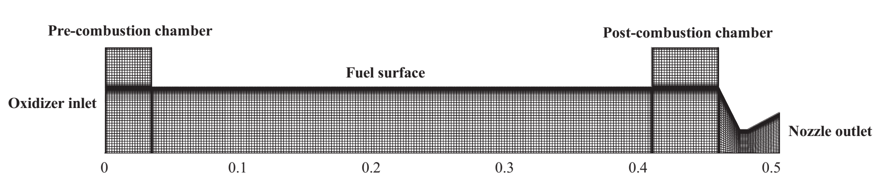

Fig. 1. Computational grid.