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Numerical analysis of combustion characteristics of hybrid rocket motor with multi-section swirl injection

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ABSTRACT

This paper is aimed to analyse the combustion characteristics of hybrid rocket motor with multi-section swirl injection by simulating the combustion flow field. Numerical combustion flow field and combustion performance parameters are obtained through three-dimensional numerical simulations based on a steady numerical model proposed in this paper. The hybrid rocket motor adopts 98% hydrogen peroxide and polyethylene as the propellants. Multiple injection sections are set along the axis of the solid fuel grain, and the oxidizer enters the combustion chamber by means of tangential injection via the injector ports in the injection sections. Simulation results indicate that the combustion flow field structure of the hybrid rocket motor could be improved by multi-section swirl injection method. The transformation of the combustion flow field can greatly increase the fuel regression rate and the combustion efficiency. The average fuel regression rate of the motor with multi-section swirl injection is improved by 8.37 times compared with that of the motor with conventional head-end irrotational injection. The combustion efficiency is increased to 95.73%. Besides, the simulation results also indicate that (1) the additional injection sections can increase the fuel regression rate and the combustion efficiency; (2) the upstream offset of the injection sections reduces the combustion efficiency; and (3) the fuel regression rate and the combustion efficiency decrease with the reduction of the number of injector ports in each injection section.

1. Introduction

Hybrid rocket motor usually utilizes liquid oxidizer and solid fuel as the propellants. Owing to this unique structure, hybrid rocket motor possesses multiple advantages [1–6] over both conventional liquid rocket motor and solid rocket motor, such as simple structure, high reliability, safety, simplified throttling and non-pollution. These advantages make hybrid rocket motor attract the attention of researchers for its potential applications [7–11] in a wide range of fields, including sub-orbital vehicles, commercial manned spacecraft and sounding rockets. However, diffusion combustion [12–14] is the intrinsic characteristics of hybrid rocket motor because the oxidizer and the fuel are separately stored and non-premixed. The fuel regression rate and the combustion efficiency of hybrid rocket motor are usually unsatisfying for these characteristics. Extensive studies have been conducted in order to increase the fuel regression rate and the combustion efficiency of hybrid rocket motor. Among the numerous proposals, multi-section swirl injection is considered to be an effective method.

In recent years, the hybrid rocket motor with multi-section swirl injection has been focused on by several researches. Experiments were conducted in [15] to study high density polyethylene (HDPE) based and paraffin based hybrid rocket motors with multi-section swirl injection method. According to this study, the HDPE fuel experiment results showed that the average fuel regression rate of the hybrid rocket motor with multi-section swirl injection was about 2–3 times higher compared with that of the motor with conventional no-swirl injection method, and the paraffin fuel experiment result was about 10 times higher. Tests focused on the average fuel regression rate and the combustion efficiency were presented in [16,17]. The results showed that the fuel regression rate was greatly improved and the combustion efficiency could even approach 1.0 in some cases. These experiments also revealed that the increase of the injector port diameter might cause a higher average fuel regression rate. In addition, Araki et al. [18] studied the effect of difference in the number and the diameter of injector ports on the average fuel regression rate of paraffin based hybrid rocket motor. The experiment results showed that grooves would form around the injector ports. The formation of the grooves was likely to be influenced by the injector flow from other injector ports. Furthermore, they also concluded that the average fuel regression rate could be controlled by

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Nomenclature

Variables

Q	rate of heat transfer
E	activation energy
t	time
ρ	density
u	velocity
e	energy
k	kinetic energy of turbulent fluctuations
ϵ	turbulence dissipation rate
Y	mass fraction
p	pressure
T	temperature
μ	viscosity
R	universal gas constant
$R_{i,r}$	rate of production of species i due to reaction r
$v'_{i,r}$	stoichiometric coefficient for reactant i in reaction r
$v''_{j,r}$	stoichiometric coefficient for product j in reaction r
M	molecular weight
$\dot{r}$	fuel regression rate
c	specific heat
A	Arrhenius pre-exponential factor
L	length
d	diameter
θ	angle
G_{ox}	oxidizer mass flux
O/F	oxidizer to fuel ratio
$\dot{m}$	mass flow rate
c^*	characteristic velocity
η	combustion efficiency
x,y,z	coordinate system

Subscripts

n	normal direction
s	fuel surface
t	throat of nozzle
e	exit of nozzle
o	oxidizer
f	fuel
b	burning
c	combustion chamber
avg	average
act	actual
th	theoretical

changing the shape of fuel grain.

The researches mentioned in the references suggest that multi-section swirl injection is an effective method to improve the combustion performance of hybrid rocket motor. However, there has been few studies conducted through numerical simulations to the best of the author's knowledge. Consequently, the majority of the discussions were on the basis of the average fuel regression rate determined by the weight loss method [19] instead of the fuel regression rate distribution determined by the combustion flow field. The combustion flow field, which could be simulated through numerical method, needs to be analysed comprehensively in order to acquire the mechanism of the multi-section swirl injection method. This paper focuses on the combustion flow field characteristics of the hybrid rocket motor with multi-section swirl injection. The combustion flow field is simulated by a steady numerical model based on a gas governing equation, a turbulence model, a two-step chemical reaction model, a fluid–solid coupling model and a regression rate model. Moreover, three-dimensional numerical simulations on hybrid rocket motors with different structures are carried out to study the influence of the number of injection sections, the position of injection sections and the number of injector ports in each injection section.

2. Model description

The propellants utilized in this study are hydrogen peroxide (HP) and polyethylene (PE). The combustion in hybrid rocket motor is an extremely complex process which involves many physical and chemical reactions [20] including turbulence, oxidizer injection, atomization, fuel pyrolysis, gasification and burning. In order to simplify the simulation process, it is considered that the oxidizer injected into the combustion chamber has already vaporized and decomposed. Besides, the radiation heat transfer is also ignored.

The ANSYS FLUENT platform with user-defined functions (UDFs) is used to solve the numerical model. The main simulation process is conducted in FLUENT solver, while the fluid–solid coupling model and the regression rate model are solved by UDFs.

2.1. Gas governing equation

The gas governing equation [21,22] of the inner flow field couples the Navier–Stokes equations with transport equations and turbulence equations. The gas governing equation can be expressed in the vector form as

$$\frac{\partial \mathbf{Q}}{\partial t} + \frac{\partial \mathbf{E}_i}{\partial x_i} = \frac{\partial \mathbf{V}_i}{\partial x_i} + \mathbf{H} \tag{1}$$

where

$$\mathbf{Q} = \begin{pmatrix} \rho \\ \rho u_j \\ e \\ \rho k \\ \rho \varepsilon \\ \rho Y_m \end{pmatrix}; \quad \mathbf{E}_i = \begin{pmatrix} \rho u_i \\ (\rho u_i u_j + p_t)\delta_{ij} \\ (e + p_t)u_i \\ \rho u_i k \\ \rho u_i \varepsilon \\ \rho Y_m \end{pmatrix}; \quad \mathbf{V}_i = \begin{pmatrix} 0 \\ \tau_{ij} \\ u_j \tau_{ij} + \lambda \frac{\partial T}{\partial x_i} \\ \mu_k \frac{\partial k}{\partial x_i} \\ \mu_\varepsilon \frac{\partial \varepsilon}{\partial x_i} \\ \rho D_m \frac{\partial Y_m}{\partial x_i} \end{pmatrix}$$

where the vector $\mathbf{H}$ is the source term concerning turbulence and combustion, p_t is the effective pressure expressed as $p_t = p + (2/3)\rho k$, Y_m is the mass fraction of the mth chemical species and τ_{ij} is the viscous stress tensor expressed as

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_1}{\partial x_1}\right)$$

2.2. Turbulence model

The realizable k–ε turbulence model [23] is chosen as the turbulence model of the inner flow field. The energy source terms of k equations and ε equations in the k–ε realizable turbulence model can be expressed as follows:

$$H_k = G_k + G_b - \rho\varepsilon - Y_m + S_k \tag{2}$$