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Parametric investigation of secondary injection in post-chamber on combustion performance for hybrid rocket motor

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ABSTRACT

The objective of this effort is to study the combustion performance of a hybrid rocket motor with the help of 3D steady-state numerical simulation, which applies 90% hydrogen peroxide as the oxidizer and hydroxyl-terminated polybutadiene as the fuel. A method of secondary oxidizer injection in post-chamber is introduced to investigate the flow field characteristics and combustion efficiency. The secondary injection medium is the mixed gas coming from liquid hydrogen peroxide catalytic decomposition. The secondary injectors are uniformly set along the circumferential direction of the post-chamber. The simulation results obtained by above model are verified by experimental data. Three influencing parameters are considered: secondary injection diameter, secondary injection angle and secondary injection numbers. Simulation results reveals that this design could improve the combustion efficiency with respect to the same motor without secondary injection. Besides, the secondary injection almost has no effect on the regression rate and fuel sueface temperature distribution. It is also presented that the oxidizer is injected by 8 secondary injectors with a diameter of 7–8 mm in the direction of 120°in post-chamber is identified as the optimized secondary injection pattern, through which combustion efficiency, specific impulse efficiency as well as utilization of propellants are all improved obviously.

1. Introduction

One of the basic structural characteristics of a hybrid rocket motor is the storage of oxidizer and fuel in different phases, most often with liquid oxidizer and solid fuel. The storage of oxidizer and fuel in different locations and phases brings many advantages, including high level safety, thrust throttling, high reliability, low cost and less environmental pollution [1–4]. Owing to these merits, the hybrid rocket motor provides promise for future aerospace propulsion applications, such as the launch vehicle booster, upper stage orbital engine, tactical missile and target missile etc. [5–10].

In the hybrid rocket motor, gaseous oxidizer flows over the solid fuel, reacts with the pyrolyzed gas close to the fuel surface and forms a turbulent, reactive boundary layer with blowing. The heat feedback, from the diffusive flame, provides the heat of pyrolysis for the thermal decomposition of the solid fuel, allowing the heterogeneous combustion process development [11]. The continual receding of the fuel surface forms a burning speed, which is called the regression rate. The regression rate, as the key aspect for hybrid rocket motor efficiency evaluation in diffusion combustion, depends on thermal energy flux spent for gasification and gasification conditions. In addition, the combustion in hybrid rocket motor actually involves tiny liquid drops in experiments. Comparison of theoretical and experimental data shows that the quasi-equilibrium being undoubtedly valid for large droplets and flat surfaces, brings to essential errors for small droplets [12]. Thus in order to have adequate data for and combustion rate of small droplets for hybrid rocket motors, it is necessary to use the non-equilibrium model [13]. So far, several efforts relented to oxidizer injecton have been performed to improve regression rate for combustion performance.

The experimental results of Lee et al. [14] showed that a higher regression rate can be achieved when the swirl flow is induced. Tests focused on the average fuel regression rate and combustion efficiency are presented in Ref. [15]. These experiments revealed that the increase of the injector port diameter might cause a higher average regression rate. The combined effect of paraffin-based fuel and swirl injectors on the regression rate enhancement have also been tested by Rakesh and Sakote et al. [16]. Besides experiments, simulation work also plays an important role in the understanding of hybrid rocket motors [17]. carried out the simulation for the regression rate by using an open source OpenFOAM code. The conclusion is that in the hybrid rocket motor the combustion

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Nomenclature

Variables

A	Arrhenius pre-exponential factor
C	specific heat
c^*	characteristic velocity
E_α	activation energy
E,F,G	vectors of inviscid fluxes
G_{ox}	oxidizer mass flux
H	enthalpy
I_s	specific impulse
K	kinetic energy of turbulent fluctuations
M	molecular weight
$\dot{m}$	mass flow rate
N	secondary injection number
O/F	oxidizer to fuel ratio
P_c	combustion chamber pressure
Q	vector of conservative variables
R	universal gas constant
$\dot{r}$	average regression rate
S	deformation tensor
T	temperature
T	time
u, v	velocity in coordinate system
x,y,z	coordinate system
α	secondary injection angle
ε	turbulence dissipation rate
η	efficiency
μ	viscosity
ρ	density
σ_k	inverse effective Prandtl numbers for k
σ_ε	inverse effective Prandtl numbers for ε

Subscripts

C_4H_6-out	C_4H_6 at the nozzle outlet
conv	convection
exp	experiment
f	fuel
g	gas
ini	initial
itf	iteration
o	oxidizer
O_2-out	O_2 at the nozzle outlet
Pri	primary injection
pyr	pyrolysis
rad	radiation
s	fuel surface
sec	secondary injection
sim	simulation
th	theoretical

chamber pressure could increase the regression rate. Paccagnella et al. [18] has carried out a numerical investigation of the behavior of a hybrid rocket motor that uses a swirl injector located at the head end of the motor. Results show the swirl injector develops the characteristic helical flow pattern that enhances the mixing of chemical species in the combustion process and thus increases the regression rate. In addition, various firing tests and numerical analysis with multi-section swirl injection in combustion chamber have been performed in Ref. [19]. The simulation results indicate that the additional injection sections can increase the fuel regression rate and combustion efficiency. Roy et al. [20] proposed a Vortex Injected Hybrid Rocket Engine concept, whose liquid oxidizer is injected tangentially to the aft end of the fuel grain and generates a bi-directional vortex flow field, has been shown to improve both the regression rate of the solid fuel and the associated combustion efficiency.

Moreover, considered the structural characteristics of the motor and the combustion situation where the upper half of the grain port is rich in oxidizer and the secondary half of the grain port is rich in fuel, an approach of applying secondary injection technology [21–23]in post-chamber is adopted in this study. The topic of this study is a numerical investigation of the combustion performance of hybrid rocket motor that uses a secondary oxidizer injector located at the post-chamber of the motor, with particular attention to the influence of several parameters. More specifically, three parameters are mainly considered: secondary injection diameter, secondary injection angle and secondary injection number.

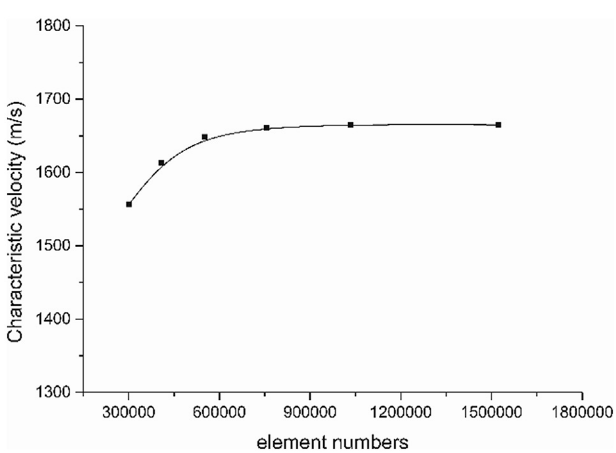

Fig. 1. Grid dependency.

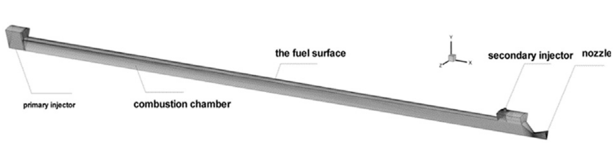

Fig. 2. Computational grid of inner flow field of 1/8.

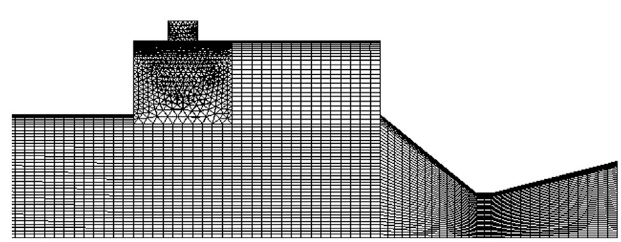

Fig. 3. The detailed grids of post-chamber.

Table 1
Combustion kinetics model [30].

Reactions	A	B	Ea/R
$C_4H_6+3.5O_2 \rightarrow 4CO+3H_2O$	8.80E+11	0	1.52E+4
$CO+0.5O_2 \leftrightarrow O_2$	3.98E+14	0	2.01E+4