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Numerical investigation on the regression rate of hybrid rocket motor with star swirl fuel grain

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ABSTRACT

Although hybrid rocket motor is prospected to have distinct advantages over liquid and solid rocket motor, low regression rate and insufficient efficiency are two major disadvantages which have prevented it from being commercially viable. In recent years, complex fuel grain configurations are attractive in overcoming the disadvantages with the help of Rapid Prototyping technology. In this work, an attempt has been made to numerically investigate the flow field characteristics and local regression rate distribution inside the hybrid rocket motor with complex star swirl grain. A propellant combination with GOX and HTPB has been chosen. The numerical model is established based on the three dimensional Navier–Stokes equations with turbulence, combustion, and coupled gas/solid phase formulations. The calculated fuel regression rate is compared with the experimental data to validate the accuracy of numerical model. The results indicate that, comparing the star swirl grain with the tube grain under the conditions of the same port area and the same grain length, the burning surface area rises about 200%, the spatially averaged regression rate rises as high as about 60%, and the oxidizer can combust sufficiently due to the big vortex around the axis in the aft-mixing chamber. The combustion efficiency of star swirl grain is better and more stable than that of tube grain.

1. Introduction

Hybrid rocket motor, which is an attempt to exploit some advantages of liquid rocket engine and solid rocket motor technology, presents a number of advantages including safety, reliability, low cost, throttling capability and minimal environmental impact. These advantages make hybrid rocket motor attractive and prospective in many fields, such as target missiles, low-cost tactical missiles, upper stage motors, boosters for launch and sounding rockets [1–3]. Especially, the successful launchings of SpaceShipOne and SpaceShipTwo spacecrafts, which adopted hybrid rocket motor as their propulsion system to accomplish a commercial sub-orbital space tourism, have accelerated the development of hybrid rocket motor [4–6].

Nevertheless, hybrid rocket motor exhibits some drawbacks during the research period. The outstanding ones among these drawbacks are low-regression rate and insufficient efficiency. The fuel regression rate of hybrid rocket motor is obviously lower than that of the solid rocket motor for its non-premixed diffusion combustion [7]. As a result, to compensate for a low fuel surface regression rate, grain may need to go from a single port to multiple ports to increase the effective burning surface area to reach the desired chamber pressure [2]. The HyFlyer suborbital launch vehicle, developed under the project Hybrid Technology Option Project (HyTOP), was powered by a 250,000 pound thrust hybrid rocket motor [8]. This motor adopted a 15 ports wagon wheel fuel grain to gain the effective burning surface area. Another 250,000 pound thrust hybrid rocket motor under the project Hybrid Propulsion Demonstration Program (HPDP), adopted a 7 ports wagon wheel fuel grain [9]. Kim et al. [10] investigated combustion characteristics of the cylindrical multiport grain of a hybrid rocket motor experimentally. But this type of grain is not an efficiency way since large fuel slivers will remain at the end of burn [1]. Besides the multiple ports grain, star grain is another way to increase the effective burning surface area [11–13]. As for the other drawback of insufficient efficiency, it's due to insufficient mixing of unreacted fuel gas and oxidizer in mixing chamber. Tian hui et al. [13] have investigated on putting an aft mixing chamber diaphragm in a hybrid rocket motor to increase the combustion efficiency by both numerical and experimental methods. Other researchers [14–16] found that a diaphragm placed along grain length can both raise efficiency and regression rate as a result of vortex flow. Nevertheless, a diaphragm will increase motor structure mass at the same time.

In 2005, Lee, et al. [17] added helical troughs to several PMMA tube grains with different pitches. This fuel grain configuration is

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Nomenclature

Variables

A	Arrhenius pre-exponential constant
a	regression rate leading coefficient
C	molar concentration of species
C^*	characteristic velocity
c	specific heat capacity
D	mass diffusion coefficient
E	activation energy
e	energy
G	mass flux
h	sensible enthalpy
k	turbulence kinetic energy in turbulence model reaction rate in combustion model
M	molecular weight
$\dot{m}$	mass flow rate
n	flux exponent
p	pressure
R	universal gas constant
r	fuel regression rate
T	temperature
t	time
u	velocity
Y	mass fraction
ε	turbulence dissipation rate
η	efficiency
λ	thermal conductivity
μ	viscosity
ρ	density
ω	net rate of production of species
ν'	stoichiometric coefficient for reactant
ν''	stoichiometric coefficient for product

Subscripts

ave	average
b	backward
c	chamber
eff	effective
f	forward
fuel	fuel
g	gas phase
n	normal direction
o	oxidizer
P	product species
p	pressure
R	reactant species
ref	reference
s	solid phase
sim	simulation
surf	surface
t	turbulence
th	theory
tot	total

adopted to simply increase the burning surface area and to try to induce swirl flow. Experimental results indicated that this helical grain can lead to an increase in regression rate up to 50%. With the development and progress of science and technology, Rapid Prototyping (RP) became a technology used to generate 3-dimentional shapes by computer control. By this technique, the fuel grains of hybrid rocket motor can be fabricated to more complex ones than conventional fuel grains extending a 2-dimentional cross-section into the third dimension. In 2011, Fuller et al. [18], researchers of the Aerospace Corporation, successfully tested small-scale motors with a multi-port helix grain and a coaxial grain which are fabricated by the material epoxy-acrylate with RP technology. They also fabricated a straight star grain and a helical star grain with the same star cross-section. As a result, with the same volume and mass of grain, the burning surface area of the helical star grain is 25% higher than the straight star grain. Additionally, the twist of the helix is expected to promote mixing. In the next 2 years, researchers of the Pennsylvania State University [19–21] noticed the potential of RP fuel grains and began to collaborate with the Aerospace Corporation. Several samples of either printed pure acrylic, printed heterogeneous paraffin/acrylic matrix, or cast paraffin grains provided by collaborators were tested in the Long Grain Center Perforated (LGCP) hybrid rocket motor. It was found that, at the same gaseous-oxygen mass flux, regression rate increases by about 270% in 1/2-tpi star swirl acrylic samples over the result of the published correlation by Zilliac and Karabeyoglu [22]. Whitmore et al. [23] from Utah State University developed a semi-analytical engineering model to describe the effects of helical fuel ports on hybrid fuel regression rates.

Although Armold et al. [19] investigated the performance of hybrid rocket motor with star swirl fuel grain experimentally and obtained the internal ballistic and regression rate; the flow field characteristics, combustion process and local regression rate distribution on burning surface inside the hybrid rocket motor with the particular non-conventional star swirl grain is still unclear. Numerical method [11, 24–30] is an effective way to study these problems with which experimental method is hard to handle. However, previous studies are mostly focus on the single tube grain, then a few multi-port grain and star grain. Few numerical investigations on the internal flow of hybrid rocket motor with the complex star swirl fuel configuration type have been reported. The main objective of this paper is to numerically investigate the flow field characteristics, combustion process and local regression rate distribution on complex burning surface inside the hybrid rocket motor with star swirl grain. The numerical model including governing equations, turbulence model, combustion model and coupled gas/solid phase formulations are presented, and then verified through the comparison between computational results and experimental data corresponding to the geometry and test conditions employed in lab-scale experiments [29,31]. The fuel grain configuration and size in Ref. [19] are adopted to this paper directly. The propellant combination is gaseous-oxygen (GOX) and hydroxyl terminated polybutadiene (HTPB) for its wide application in numerical research field of HRM. The numerical simulations are performed for two kinds of fuel grain configurations including tube and star swirl shapes in order to make a contrast. The influences of oxidizer mass flux and fuel type on the regression rate are then presented and discussed based on the simulation results.

2. Numerical model

2.1. Governing equations

For the complex configuration of the star swirl grain, the three dimensional Navier–Stokes equations are applied to describe flow processes inside the hybrid rocket motor. The vector form of the equations are represented as follows: