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Diameter and position effect determination of diaphragm on hybrid rocket motor

Xingliang Sun, Hui Tian, Guobiao Cai *

School of Astronautics, Beihang University, 100191, China

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ABSTRACT

This study is aimed to determine and better reveal the mixture enhancement and regression rate distribution of hybrid rocket motor with diaphragm by numerical approach. A numerical model based on the computational fluid dynamics software is built to simulate the flow and combustion inside the motor. Four firing tests of the motor, including one without diaphragm and three with diaphragm, are conducted on a standard experimental system and also used as a reference for numerical simulation, the consistency between the simulation and experiment demonstrates that the numerical approach is an effective method to study the diaphragm effect on the motor performance. The flow field characteristic and regression rate distribution inside the hybrid rocket motor are then calculated to analyze the effect of position and diameter of the diaphragm. The results indicate that the diaphragm almost have no effect on the regression rate before it. However, the regression rate after the diaphragm has a strong dependence on the position and diameter of the diaphragm. As the diameter decreases and the position moves backward, the regression rate increases larger and larger, this is mainly due to the augmentation of the eddy generated by the diaphragm, which enhances the heat feedback transferred to the grain surface. When the diameter of diaphragm located at middle of grain decreases from 50 mm to 20 mm, regression rate is increased from 0.30 mm/s to 0.57 mm/s. The use of the diaphragm does cause a combustion efficiency improvement; the maximum combustion efficiency is enhanced to 98.9% from lower than 90% of the motor with no diaphragm. The increasing amplitude displays a square relation with the diameter decrease, since the entrainment of the eddy make the reactants mix sufficiently to release more energy inside the motor.

1. Introduction

The hybrid rocket motor utilizes liquid oxidant and solid fuel as the propellant. This characteristic makes the hybrid rocket motor distinct from the conventional solid or liquid rocket motor. The hybrid rocket motor has many advantages such as the capability of restart, thrust throttling, simplicity and safety. It has a broad range of applications including the sounding rocket, tactical missile and space engines [1–6]. However, due to the feature that the oxidant and solid fuel is stored separately, the combustion inside the motor belongs to the classical diffusion flame, the hybrid rocket motor suffers low regression rates and combustion efficiencies [7–9]. These drawbacks have limited its widespread application. With great interests of the attractive feature and the amelioration of the drawbacks of the hybrid rocket motor, many efforts have been made to improve the low regression rate and low combustion efficiency of the hybrid rocket motor [10–19].

The regression rate is a key parameter for the study and design of the hybrid rocket motor. Various experimental and theoretical methods have been proposed to enhance the low regression rate of the hybrid rocket motor. Risha and Evans [20–23] have studied the enhancement effect of the aluminum on the regression rate by series of firing tests, they found that the nanometer-sized aluminum has the highest enhancement on the regression rate, a 20% weight addition of aluminum can increase the regression rate by 40%. Yuasa et al. [24] have carried out some hybrid rocket motor firing tests with a swirl injector to study the effect of swirl strength on the regression rate, the results indicated that the average regression rate shows an increase up to 200% as swirl number increases. However, the higher regression rate is mainly localized near the inlet of fuel port, because the swirl strength is decreased with the increase of the axial distance. Knuth et al. [25] have designed a so-called vortex tube method, so that the swirl strength can reside significantly longer over the entire fuel port, this method consequently lead to a substantial

* Corresponding author.
E-mail address: cgb@buaa.edu.cn (G. Cai).

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Nomenclature

Variables

A	Arrhenius pre-exponential constant
A_t	Nozzle throat area
D_d	Diaphragm port diameter
D_g	Grain port diameter
E_a	Activation energy
F_t	Motor thrust
G	Oxidizer flux
h	Heat transfer coefficient
L_d	Diaphragm axial distance
L_g	Grain port length
λ_d	Ratio of diaphragm port diameter to grain port diameter
λ_l	Ratio of diaphragm axial distance to grain length
$\dot{m}$	Mass flow rate
η_{c*}	Combustion efficiency
p_c	Chamber pressure
ρ	Density
$\dot{Q}$	Rate of heat transfer
r	Grain port radial
$\dot{r}$	Regression rate
R_o	Universal gas constant
t	Test time
T	Temperature subscripts:
after	After the diaphragm
before	Before the diaphragm
conv	Convection
end	End of test
exp	Experiment
f	Fuel
g	Gas phase
ini	Initial
itf	Iteration
ox	Oxidizer
pyr	Pyrolysis
rad	Radiation
sim	Simulation
s	Surface
tot	total
th	theoretical

increase in regression rate up to 150% compared to that without swirl. Karabeyoglu et al. [26] found and studied the higher regression rate of the paraffin fuel used for hybrid rocket motor, the test data showed that the regression rate is about 3 times higher than that of the HTPB fuel. But they also found the paraffin has a lower combustion efficiency. For the improvement of the low combustion efficiency of the hybrid rocket motor, one common method is to introduce a diaphragm inside the motor [27–29]. Both combustion efficiency and regression rate can be improved by the diaphragm, since that induces a large increase of the turbulence level in the combustion chamber and enhances the mixing of the propellants and the heat transfer to the grain surface. However, to the best of the authors' knowledge, many studies about the effect of diaphragm is focused on the combustion efficiency. There has been few work done on the effect of the diaphragm parameters on the both regression rate and combustion efficiency, especially on the effect of the diaphragm position. So the numerical and experimental research on the influence of the one-hole diameter and axial position of the diaphragm to the regression rate and combustion efficiency is considerably meaningful.

The paper is aimed to combine the numerical simulations and firing tests to study the effect of the diaphragm on the regression rate and combustion efficiency, and to better reveal the diaphragm effect and regression rate distribution by analyzing the internal flow field characteristics obtained by the established numerical model inside the motor. For this purpose, the work is carried out by following steps. First, an experimental hybrid rocket motor is designed to carry out firing tests with/without the diaphragm, and to provide references for the numerical results. Second, a numerical model is established to simulate the combustion and flow inside the hybrid rocket motor with the diaphragm. The numerical model is validated with the experimental data, and then series of simulation cases are defined to determinate the flow field parameters and regression rate distribution. Finally, the effect of position and diameter of the diaphragm on the regression rate and motor performance is analyzed and discussed.

2. Experimental setup

2.1. Motor configuration

In order to carry out the firing tests of hybrid rocket motor with/without the diaphragm, the hybrid rocket motor components and the diaphragm are designed and manufactured. The physical composition of the motor is shown in Fig. 1. The motor is a reloadable system and is assembled by injection panel, pre-chamber, igniter, combustion chamber, aft-chamber and nozzle. The combustion chamber has an inner diameter of 100 mm and length of 500 mm, it has the capability of housing different combinations of the grain and diaphragm. In this study, the grain has an initial port diameter of 50 mm. The injection panel, igniter and nozzle is given out in Fig. 2. The nozzle has an expansion ratio of 2.96 with a nozzle throat diameter of 18 mm. The solid fuel is the grain with an initial grain port diameter of 50 mm and length of 500 mm.

2.2. Experimental schedules

The experiment uses the polyethylene (PE) as the solid fuel and the liquid 90% hydrogen peroxide (90HP) as the oxidizer. The 90HP is ignited by an ignition motor, the structure chart of the ignition motor is shown in Fig. 3. The ignition motor is composed by ignition chamber and powder ring. To carry out firing tests, an electronic ignition signal is generated by the control system to start the ignition motor. The mass flow rate of the oxidizer is controlled by the venturi, so that it can be kept constant over the entire firing test.

The diaphragm applies the silica phenolic resin material, considering it is often used as a high temperature resistant and

Fig. 1. Physical composition of hybrid rocket motor.