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Numerical study on solid-fuel scramjet combustor with fuel-rich hot gas

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ABSTRACT

Solid-fuel scramjet combustor with cavity faces challenges of ignition and flame holding. In the current study, a novel concept, solid-fuel scramjet combustor with fuel-rich hot gas, is proposed. The Reynolds-average Navier–Stokes (RANS) equations coupled with the SST $k-\omega$ turbulence model and the second-order spatially accurate upwind scheme are employed to calculate its flow field. The feasibility of the solid-fuel scramjet combustor with fuel-rich hot gas is studied based on the validation of numerical method. The comparison of the performance is made between the combustor with fuel-rich gas and the combustor with cavity. Various parameters, namely excess air coefficient of gas generator and mass flow rate of fuel-rich gas, are studied, and their effects on the combustion efficiency, total pressure recovery and fuel regression rate are analyzed. This is the basic study for experiments of a solid-fuel scramjet combustor with fuel-rich hot gas.

1. Introduction

The liquid-hydrogen fueled [1] NASA X43A scramjet performed two self-propelled flights with record-breaking speed in 2004 [2,3], arousing researchers' intense interest in scramjets. Compared with liquid-fuel scramjets, solid-fuel scramjets may present the same advantages as other solid-fuel motors, namely simple structure, higher reliability and energy density level. In other words, there is no need for complex fuel supply systems or moving parts. Therefore, solid-fuel scramjets' system may be safer, designed more compact and easier to store propellant for a long-term mission. Objectively, solid-fuel scramjets also have some drawbacks, maneuverability disadvantage and difficulty in re-ignition, for example. Nowadays, much more attention is paid to liquid-fuel scramjets [4–10], but the research on solid-fuel scramjets is still in its infancy. Most achievements in solid-fuel scramjets are summarized below.

The pioneering experimental studies on the solid-fuel scramjets were conducted by Witt [11] and Angus [12]. Witt [11] used polymethylmethacrylate (PMMA) as solid fuel, pointing out that the flame stabilization could be achieved. However, the flame holding, combustion efficiency and mixing efficiency were sensitive to the structure of combustor chamber. Angus [12] achieved a combustion efficiency of up to 57% in the experiments. Later, Vaught et al. [13] demonstrated the feasibility of solid-fuel, dual-mode combustion ramjets at a design point of Mach number 6 with the altitude being 24.4 km. However, this kind of ramjets increases the complexity of inlet design. Then Ben-Yakar et al. [14,15] achieved self-ignition and sustained combustion of the PMMA fuel without external aid in a series of experiments. In their experiments, a cavity was employed to stabilize the flame. The consumption of solid fuel triggered the disappearance of the cavity. As a result, the flame quenched. Cohen and Natan [16] further investigated the solid-fuel scramjet with cavity. An initial relation concerning the mean fuel regression rate and entrance flow parameters was established. Ben-Arosh et al. [17] carried out a two-dimensional axisymmetric simulation of solid fuel combustion in a supersonic flow using a simplified two-step and six-species mechanism, examining the effects of inlet airflow Mach numbers and structural parameters on the combustor performance. Wang et al. [18] investigated changes of specific thrust numerically during the operating process of solid-fuel scramjet combustor, reporting that the specific thrust decreased continuously until the extinction of flame. Saraf and Gany [19] studied the performance of the scramjet with metalized or no metalized solid fuel, coming to a conclusion that solid fuel containing aluminum powder could increase the specific thrust and decrease the specific impulse of the scramjet.

In the experiments mentioned above, solid-fuel scramjets could operate for seconds by employing a cavity to achieve flame holding. In fact, the cavity configuration (CWC in short), as shown in Fig. 1, faces some challenges [20]. One is the difficulty in ignition and flame holding in the high-speed airflow. Another one

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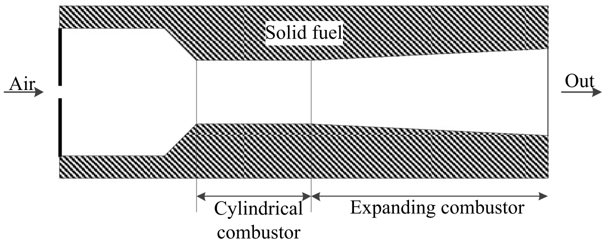

Fig. 1. Solid-fuel scramjet combustor with cavity (CWC in short).

is the low combustion efficiency of solid fuel in supersonic flow. Moreover, the sensitivity of performance to internal structures of combustor is also worth attention. Among these challenges, the basic and principal issue is to overcome the difficulty in ignition and long-time flame holding. The capability of the CWC[1] to achieve ignition and flame holding is sensitive to the length-to-depth ratio of the cavity [15]. Experimental researches indicate that the CWC will flame out after about ten seconds [14,15,18] owing to the disappearance or distortion of the cavity. Remains of the solid fuel grain are a waste. Short operating time and waste of solid fuel grain may prevent its application. Therefore, it is necessary to improve flame stability. To tackle these problems, Lv et al. [20] proposed a new scramjet configuration using solid fuel, namely solid-fuel rocket scramjet, rather than investigating improvement in the CWC.

Differently from the method of Lv et al., we propose a novel approach that employs fuel-rich hot gas to achieve ignition and flame holding in place of the cavity in a solid-fuel scramjet to improve the CWC. The combustor configuration is shown in Fig. 2 (CWG in short). It consists of a cylindrical combustor and an expanding combustor. Fuel-rich hot gas is injected into the combustion chamber from the back-step.

The fuel-rich hot gas, promoting pyrolysis of solid fuel because of its high temperature, can be produced by a gas generator. Moreover, the pilot flame, facilitating ignition and flame holding, generated from combustion of fuel-rich gas and oxygen can last for a long time unless the gas generator is turned off. So the ignition and flame holding are less troublesome and the operating time of a solid-fuel scramjet may last longer. A C_2H_4/O_2 gas generator is employed to produce fuel-rich hot gas for this numerical study.

In the following study, the CWG[2] will be investigated numerically. In section 2, the geometric dimensions are provided, as well as the numerical method, fuel regression rate model and boundary conditions. In section 3, the model validation and grid independence analysis are both conducted. Then flow field characteristics and flame characteristics are discussed respectively. In addition, comparisons of performance are made between the CWG and CWC. In section 4, the effects of the excess air coefficient of gas generator and mass flow rate of fuel-rich gas on performance are studied. In section 5, some valuable conclusions are summarized.

[1] Solid-fuel scramjet combustor with cavity.
[2] Solid-fuel scramjet combustor with fuel-rich hot gas.

Table 1
Governing equation parameters.

Variables	Φ	Γ	S_Φ
Continuity equation	1	0	0
Momentum equations	μ_i	u	$\partial p/\partial x_i + S_i$
Energy equation	T	k/c	S_Γ
Species equation	C_s	$\rho\omega_s$	S_s

2. Models and method

2.1. Geometric dimensions

Structural parameters of the CWG are consistent with that of Ben's experiments [14] at the third second for the comparison of the performance. The length and diameter of cylindrical combustor are 85 mm and 21.1 mm respectively. The total length of the combustor is 170 mm, and the diameter of air inlet is 12.5 mm. The divergence angle of expanding combustor is three degrees.

2.2. Numerical method

ANSYS FLUENT 13.0 [21] is employed to simulate the two-dimensional flow field of a solid-fuel scramjet combustor. User-defined function (UDF) is developed to obtain the real-time fuel regression rate and the mass flow rate of solid fuel. The same approach was used in the study of literature [22,23].

A 2D-axisymmetric solver is used in the simulation [23]. The corresponding Reynolds-averaged Navier–Stokes equation is given as follows

$$\frac{\partial(\rho_u\Phi)}{\partial x}+\frac{1}{r}\frac{\partial(r\rho_v\Phi)}{\partial r}=\frac{\partial}{\partial x}\left[\Gamma\frac{\partial\Phi}{\partial x}\right]+\frac{\partial}{\partial r}\left[r\Gamma\frac{\partial\Phi}{\partial r}\right]+S_\Phi \quad (1)$$

where Φ is general variable, which can represent u, v, w and T, etc. Γ is the general diffusion coefficient. S_Φ is the generalized source term. For specific equations, Φ, Γ, and S_Φ have specific forms, as shown in Table 1.

The Reynolds stress is closed with SST k–ω model [24]. The SST k–ω model is a combination of the Wilcox 1988 k–ω model in the near wall region and the standard k–ε model in the detached regions, and it is suitable for mixing layer and jet flow problems, as well as insensitive to initial values [25,26].

2.3. Chemical kinetic

HTPB solid-fuel samples are chosen for the numerical simulations because they are characterized [27] for its wide use in composite propellants. Specifically, they are binders commonly found in solid fuels. In addition, a series of experimental studies were conducted with HTPB-based fuels [18] under supersonic flow. In this work, it is assumed that the pyrolysis of HTPB only produces C_4H_6 [28]. The combustion process of C_4H_6 is based on a global one-step irreversible reaction mechanism as follows

$$C_4H_6 + 5.5O_2 \rightarrow 4CO_2 + 3H_2O$$

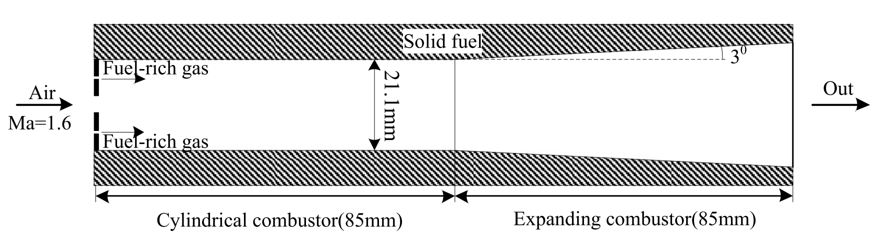

Fig. 2. Solid-fuel scramjet combustor with fuel-rich hot gas (CWG in short).

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