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Numerical investigation on cavity structure of solid-fuel scramjet combustor

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ABSTRACT

The influences of miscellaneous combustor structures for solid fuel scramjet combustion on the performance are investigated, including a detailed interaction analysis between shocks/waves and combustion. Hydroxyl-terminated polybutadiene is chosen as the solid fuel with the non-premixed equilibrium probability density function combustion model. The results show combustion enhancement when structure of combustor is modified. The radical emphasis is to examine the sensitivity of the properties due to variations on the length-to-depth ratio of cavity, aft wall angle, and offset ratio. It is noted that there is an appropriate structure of cavity ($L/D=4$, $\theta=45^\circ$, and $D_d/D_u=1.25$–1.5) regarding the combustion efficiency, total pressure loss and specific impulse. The observation of function for combustor components provides instructional insight into the design considerations for a combustor of a solid-fuel scramjet.

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1. Introduction

As we know, the hypersonic phenomena become significant with the flight Mach number above 5, which may reduce the performance of conventional ramjet engines with a subsonic-flow combustion chamber. In subsonic ramjet, as passing through a series of oblique and normal shocks, the flow comes into a considerable decrease in the velocity form high Mach number to subsonic. The reduction of the flow velocity accompanies a significant raise in the static temperature, which brings a problem that before the dissociation temperature is reached, only a limited heat can be added to the flow. Meanwhile, there is a significant decrease in the total pressure, making a loss in the flow thrust potential. Compared with the subsonic ramjet, supersonic ramjet is out of a normal shock which consequently leads to lower static temperature and higher total pressure recovery, thus, making the scramjet a preferable propulsion system for hypersonic flight missions. The scramjet engine can be powered by either solid or liquid fuels. The use of solid fuel could benefit the scramjet with its good characteristics: acceptable total pressure losses for the introduction of fuel; high-energy and high-density resulting in a more compact system; simplicity eliminating problems associated with fuel storage and feeding systems in liquid scramjet; good thermal environment avoiding combustion against wall; more safety; convenient storage for long duration, readiness upon demand. Hence, solid fuel scramjet (SFSCRJ) engines possess all prosperity of solid fuel-oriented vehicles and enable a low-cost propulsion system.

The solid fuel scramjet was demonstrated both theoretically and experimentally. Direct-connected tests were also successfully performed by many researchers. The initial experimental study was conducted by Witt [1] and Angus [2], respectively. The experiments of Angus [2] had a duration of 12.5 s and achieved a combustion efficiency of up to 57%, indicating the possibility of application of SFSCRJ. Ben-Yakar et al. [3,4] were the first to demonstrate the self-ignition and sustain combustion of the polymethyl methacrylate (PMMA) fuel with no external aid in static tests

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simulating flight Mach numbers of 5–6 at high altitude of 24.4 km. By making use of the fuel transparency, Ben gave the limits of flame holding experimentally. In Cohen-Zur and Natan [5]' experiments, the self-ignition and flame holding characteristics were observed to be consistent with the results from Ben-Yakar et al.'s work [3,4]. In the experiments of Saraf and Gany [6], it was concluded that metalized solid-fuel scramjet combustor had slightly higher fuel mass flow rate than the non-metalized one. Theoretically, Jarymowycz et al. [7]'s numerical simulation for a two-dimensional solid-fuel cylindrical chamber combustion proved that there was a distinct flame region over the fuel sample and that both inlet temperature and pressure had a strong influence on the burning rate. However, at a higher pressure, the energy released by combustion was not sufficient to further raise the crossflow temperature, consequently causing a slight influence on the burning rate. Ben-Arosh et al. [8] carried out a two-dimensional axisymmetric turbulent simulation with two-step and six-species reactive flow model. The sensitivities of the combustor performance to the flight Mach number, combustor inlet Mach number, combustor size, step height, and fuel grain length were examined.

Most previous theoretical studies of SFSCRJ focused on reliable of the CFD models and the simple combustion chamber. Thus, the structure of the combustor was rarely analyzed for its complex internal shapes and high computational cost. In scramjet combustion, the flow experiences a sudden expansion causing a drop in temperature and an increase in Mach number. Moreover, the reattachment length is shorter in supersonic than in subsonic flow. Under these conditions, the flameholding is of importance due to the lessened residence time in SFSCRJ. Designing a flameholding zone comprising an inlet step and a backward facing step to an optimized diameter can reduce the defects of these conditions. As the length of recirculation zone is determined by the cavity length and the Mach number is relatively lower, the internal area dimensions should be well designed to avoid thermal choking and maintain supersonic flow during combustion. The present investigation aims at improving the fundamental understanding of cavity-based flameholding combustor in SFSCRJ. The work conducts a detailed analysis on the various cavity-based combustor structures. The chamber is divided into three sections: cavity section, cylindrical section and diverging section. The cavity is characterized by several parameters including: length-to-depth ratio of cavity (L/D), aft wall angle (θ) (defined as the angle relative to the horizontal wall), and offset ratio (D_d/D_u). In SFSCRJ, the fuel is hard to be mixed with the oxygen in the supersonic mainflow, compared with the liquid one. In this condition, the cavity is fuel rich zone, which plays a critical role to have the fuel mixed with the oxygen upon the shear layer that spans the cavity. The length of cavity limits the resident time for mixing. Meanwhile, the cavity provides a turbulence boundary layer, which will benefit the flow stability by diminish the separation possibility induced by the interaction between shock waves and boundary layer. The L/D and D_d/D_u determine the volume of cavity together. The aft wall angle determines the separation point on the aft wall and the drag in cavity. Therefore, a strong interdependence appears to exist between the desired cavity-based combustor performance parameters and the cavity L/D ratios, aft wall angle (θ), and offset ratio (D_d/D_u).The investigations on the flow field and quality of combustor are conducted. The analysis mainly focuses on the velocity field, temperature field, thermal choke, shock train, total pressure loss, combustion efficiency, and specific impulse. A better understanding of the function of each section and components will benefit the investigation of SFSCRJ performance.

2. Mathematic and physical models

A 2-D axisymmetric and the Farved averaged N–S equation is used.

$$\frac{\partial U}{\partial t}+\frac{\partial F}{\partial x}+\frac{\partial G}{\partial y}=\frac{\partial H}{\partial x}+\frac{\partial R}{\partial y}+S \tag{1}$$

Here $\boldsymbol{U}$ is the conservative variable vector. The variables used are the density ρ, the velocity components u, v, the total energy E, and Y_i is the mass fraction of species i. $\boldsymbol{F}$, $\boldsymbol{G}$ are inviscid flux vectors and $\boldsymbol{H}$, $\boldsymbol{R}$ are viscous ones in x-, y-directions, respectively. $\boldsymbol{S}$ is a source vector resulting from combustion reaction. The detailed descriptions for the notions are presented as follows:

$$U=\begin{bmatrix}\rho\\ \rho u\\ \rho v\\ \rho E\\ \rho f_1\\ \rho f_2\\ \vdots\\ \rho f_{Ns}\end{bmatrix}\quad F=\begin{bmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ (\rho E+p)u\\ \rho u f_1\\ \rho u f_2\\ \vdots\\ \rho u f_{N_s}\end{bmatrix}\quad G=\begin{bmatrix}\rho v\\ \rho uv\\ \rho v^2+p\\ (\rho E+p)v\\ \rho v f_1\\ \rho v f_2\\ \vdots\\ \rho v f_{N_s}\end{bmatrix}$$

$$R=\begin{bmatrix}0\\ \tau_{xx}\\ \tau_{xy}\\ u\tau_{xx}+v\tau_{xy}+K\frac{\partial T}{\partial x}+\mu\sum_{i=1}^{N_s}h_i\frac{\partial f_i}{\partial x}\\ \rho D\frac{\partial f_1}{\partial x}\\ \rho D\frac{\partial f_2}{\partial x}\\ \vdots\\ \rho D\frac{\partial f_{N_s}}{\partial x}\end{bmatrix}$$

$$S=\begin{bmatrix}0\\ \tau_{yx}\\ \tau_{yy}\\ u\tau_{yx}+v\tau_{yy}+K\frac{\partial T}{\partial y}+\mu\sum_{i=1}^{N_s}h_i\frac{\partial f_i}{\partial y}\\ \rho D\frac{\partial f_1}{\partial y}\\ \rho D\frac{\partial f_2}{\partial y}\\ \vdots\\ \rho D\frac{\partial f_{N_s}}{\partial y}\end{bmatrix}$$

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