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Numerical and experimental investigations of single-element and double-element injectors using gaseous oxygen/gaseous methane

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ABSTRACT

The objective of this study is to investigate the effects of fuel/oxidizer (F/O) momentum ratio on the mechanism of mixing and combustion of single-element and double-element shear coaxial injectors numerically and experimentally using gaseous oxygen/gaseous methane (GO_2/GCH_4) and non-intrusive optical diagnostics technique based on planar laser induced fluorescence (PLIF). Instantaneous OH-PLIF images demonstrate that the flame with higher F/O momentum ratio exhibits appearance characteristics with more obvious wrinkled shear layers, extinction and kernels events. Simulation and time-averaged results show that with the increase of F/O momentum ratio at the condition of fixed total mass flow rate, the initial combustion position becomes closer to the front of the chamber. The large mass flow rate of the double-element combustor is beneficial to the thermal protection of the chamber wall. Based on the high-speed images and velocity distribution obtained from numerical data, it is detrimental for the propagation of the flame front at the injection condition of high F/O momentum ratio. In addition, according to the infrared thermal pictures, the flame outside the chamber becomes broader with the increase of F/O momentum ratio, and the plume of double-element combustor will challenge the thermal protection around the equipment. Moreover, new methods are applied in this paper to extract the flame boundary of the OH-PLIF diagrams and to calculate the number of the pixels of the plume from infrared thermal imager results.

1. Introduction

Injectors are crucial parts which can significantly affect the injection and combustion performance of rocket engine [1–3]. The main structures of injectors include shear coaxial injectors, swirl coaxial injectors, impinging injectors, etc. Swirl injectors have more efficient mixing and combustion [4–6], together with more complex structure. Shear coaxial injectors have simpler geometries and better heat environment [7–10] in comparison with other forms of injectors. Furthermore, the velocity difference of their inner and outer injectors, especially for gas combinations of propellants, can enhance the mixing of oxidizer and fuel, which allows them to improve the combustion efficiency of the entire burner.

As a sanitary hydrocarbon fuel, methane has distinct advantages in many aspects over other classical propellants. On the one hand, among all hydrocarbon fuels, liquid methane has the highest specific impulse and the smallest viscosity, along with the inexistence of coke and carbon deposition. On the other hand, the price of methane is 1/70 of liquid hydrogen, and 1/3 of kerosene. Moreover, the volume and quality of the methane tank is far less than the liquid hydrogen storage tank, for the reason that the density of liquid methane is six times that of liquid hydrogen. Above all, gaseous oxygen/gaseous methane (GO_2/GCH_4) engines with superior performance, high reliability and outstanding economic efficiency can be one of the future directions of aerospace propulsion [11–15].

To date, a considerable number of studies have been conducted on the characteristics of coaxial injectors using GO_2/GCH_4 as propellants. The academic circles have focused their attention mainly on the mechanism of the combustion and flow of this kind of injectors with high-precision numerical simulation methods and advanced optical diagnostic measurement techniques. Generally, advanced computational fluid dynamics (CFD) method can be applied to predict the combustion behaviors before practical experiments. At present, the studies on the reaction kinetics of GO_2/GCH_4 have been quite mature, and the detailed reaction mechanism of methane oxidation is GRI_Mech3.0 reaction model [16,17]. In view of the large scale of the detailed reaction mechanism, a number of semi-detailed or simplified chemical kinetic mechanisms have been developed [18]. Researchers from Beihang University applied some of the classical mechanisms to adaptive verification by using

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the same injector and chamber [16,17], and discovered that the 13 components-18 steps reaction mechanism was more suitable for the simulation of GO_2/GCH_4 rocket engines after considering the computational cost and precision of the results. Furthermore, the 'Y mechanism' proposed by Dong Gang [19] was a good reflection of the actual situation of combustion, and can provide information of free radicals and intermediates in the combustion process.

Compared with the numerical researches, the content of experimental studies based on optical diagnostic techniques is more abundant. Santoro [20,21] from Pennsylvania State University (PSU) measured the distribution of OH radicals in the combustion chamber with quartz glass window by PLIF, and detected that it was consistent with the results of simulation. With the help of PLIF technique, extensive investigations of single-element gaseous injector have been carried out by probing the distribution law of the OH groups, including the combustion characteristic of GO_2/GH_2 coaxial injector [22], the differences of flow field between coaxial injector and swirl injector [23], the comparison of two kinds of propellants combinations, which were GO_2/GH_2 and GO_2/GCH_4 [24], etc.

The OH groups have a long residence time and are widely distributed in the combustion zone. The position with peak value of OH groups corresponds to the maximum heat release rate area. Large numbers of investigations have shown that OH radicals can be used as a valid sign of the flame area, and the flame district is very close to the chemical reaction zone. Therefore, the boundary of OH groups can be considered as flame front [25–29] and it is of great significance to explore the techniques to extract the boundary of OH images.

However, actual rocket engines always have complex head cavities consist of multi-elements injectors. So far, few attempts have been made to investigate the combustion and flow field characteristics of multi-element GO_2/GCH_4 shear coaxial injectors using PLIF, which can help to validate the accuracy of the chemical mechanism applied to numerical researches. In addition, F/O momentum ratio is a key parameter which can seriously affect the mixing and combustion performance of the whole engine. Therefore, the influence of this crucial factor on the combustion characteristics of shear coaxial injectors needs to be further explored by means of non-intrusive optical diagnostics techniques. Former code used for extract the flame front of OH-PLIF images, such as level set and nonlinear diffusion filtering algorithms [22], which will either consumes too much computing resources or need to adjust the parameters for different images during the processing period. Hence, developing an adaptive algorithm for extracting the flame boundary of OH-PLIF images will remarkably improve the efficiency of the studies.

This paper aims to examine the influence of F/O momentum ratio on the combustion characteristics of single-element GO_2/GCH_4 shear coaxial injector and to preliminary observe the working performance of double-element GO_2/GCH_4 shear coaxial injectors combustor (hereinafter referred to as double-element combustor) using combined optical diagnostic devices, including PLIF, high speed camera and infrared camera. A series of numerical simulations have been conducted simultaneously to compare with the results of the actual flames. Meanwhile, a new way to obtain the flame edge by applying fuzzy local information C-Means (FLICM) algorithm [30] to the extraction of flame boundary of OH-PLIF images, which is superior to previous algorithms, was conducted during this research.

2. Simulation model and conditions

2.1. Numerical methods

Compared to those detailed chemical mechanisms which will take too much computing resources, the more efficient 13 components-20 steps reaction mechanism used in this investigation is a good reflection of the actual situation of combustion, and can provide information of free radicals and intermediates in the combustion process [19].

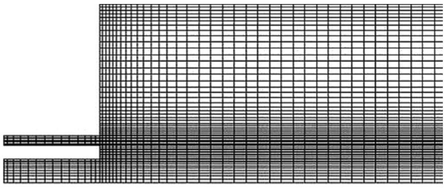

Fig. 1. Two-dimensional sketch map of single-element combustor mesh model.

The Reynolds-Averaged Navier–Stokes (RANS) numerical method of gas combustion should be discretized by the finite volume method in time, and the format of this application was second-order upwind in space. Furthermore, the equations of component, momentum, continuity, and energy were solved separately, while standard two-equation $k - \varepsilon$ model was used as the turbulence model. The chemical reaction rate was determined by the Arrhenius formula, and the Eddy-Dissipation-Concept (EDC) model was chosen for simulating the interaction between the chemical reaction and the turbulent flow. The format of convection term and diffusion term were second-order upwind and central difference, respectively. The LU implicit algorithm was selected as the solver.

2.2. Mesh model

Fig. 1 and Fig. 2 are the schematic drawings of the grid models used as computational domain for single-element and double-element injector, respectively. As a result of the actual combustor applied in this study was a cylindrical transparent quartz glass without nozzle, the numerical simulation was only performed on the front section of the combustion chamber. In order to improve the computational efficiency, a half-plane two-dimensional axisymmetric grid model was used for the single-element injector (Fig. 1), while the double-element model took a quarter of a periodic three-dimensional mesh (Fig. 2). Appropriate mesh refinement was performed in the vicinity of the combustion chamber wall, the jet panel and the shear layer. For specially explanation, different single injectors have different sizes, Fig. 1 is only a diagrammatic sketch to reveal the structure of the grid.

2.3. Boundary conditions

The entrance boundary conditions of gas–gas injectors were set to the mass inlet boundary entrance based on design value and experimental data. The temperature of methane and oxygen was set to 300 K. Define turbulence intensity as $I = \mu'/\mu_m$, (μ' is the root-mean-square (RMS) value of velocity fluctuation, μ_m is the average velocity of entrance), which was set to be $I = 5\%$ according to past experience [31,32]. The outlet of the combustion chamber was set as the static pressure outlet, which was the relative value of the working pressure. The combustion chamber wall was set to adiabatic boundary without slip.

3. Experimental setup

3.1. Burners and flames

The burners geometry used in this study are shown in Fig. 3, which were similar to the structures of the experimental devices used in previous studies [22,30]. They were constructed using a stainless steel head cavity and a cylindrical transparent quartz glass chamber. As can be seen in Fig. 3(a), for the single-element combustor, oxygen entered the injector along the axis from the