Numerical Study of Non-Equilibrium Plasma Assisted Combustion on Spacecraft Rocket Engine

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Abstract. The non-equilibrium plasma has unique advantages in ignition and combustion. In this paper, the plasma-assisted combustion scheme of the spacecraft rocket engine is designed. The numerical simulation method is used to study the influence of non - equilibrium plasma on the combustion in GH2/GO2 single co-axial injector rocket engine. Mainly to consider the plasma chemical kinetics, the discharge generated O, H and OH are added to the flow field as source term. The simulation results show that the temperature in the axial area increases with the increase of the chemical reaction rate in the combustion chamber, and the mixing effect of hydrogen and oxygen can be improved.

1. Introduction

With the increasing frequency of human space activities, personnel safety and environmental safety have attracted more attention. Conventional spacecraft rocket engine adopt hypergolic propellant such as UDMH/ N_2O_4 , which is toxic and environment harmful. Based on these factors, replacing toxic propellant with green non-toxic propellant hydrocarbon is the inevitable trend of aerospace propulsion [1].

Because of the small number of sprayer units, short residence time of propellant, and pulse mode of spacecraft rocket engine, the performance of atomization and mixing is low in the combustion chamber that is not conducive to the full combustion of propellant. This result will reduce the engine combustion efficiency, thereby shorten the service life of the spacecraft, so advanced technology is needed to improve the engine combustion efficiency.

In harsh working conditions, plasma has the potential to improve the combustion efficiency, expand the range of flame stabilization, shorten the ignition time, stabilize the flame, as a result, plasma assisted ignition (PAI) and plasma assisted combustion (PAC) are widely concerned[2]. Dielectric barrier discharge, nanosecond pulse discharge, radio frequency discharge and microwave discharge are widely used in PAI and PAC research, and have achieved satisfactory results [3]. Research results show that the plasma generated by the dielectric barrier discharge contains a large amount of active particles. The active particles can accelerate the rate of combustion chemical reaction and increase the flame propagation rate, so that the oxidation reaction of the fuel can occur under extreme conditions, and the stable combustion range of the fuel can be expanded[4],[5]. The application of plasma technology in the spacecraft rocket engine, for the engine special working environment and performance requirements, can promote the development of spacecraft rocket engine technology.

The time scale of the plasma chemistry is in the order of ns, the time scale of the combustion phase is in the order of μs, and the self-sustaining combustion is in the order of ms. Considering the plasma chemistry and combustion coupling process, will consume a lot of computing resource. S.M.Starikovskaya[6] and Han[7] decouple the discharge process from the ignition process in their simulations, and then, on the basis of discharge results, it is taken as an initial condition into the flow field to observe the effect of the plasma generated by discharge on the combustion.

In this paper, the influence of non-equilibrium plasma on the combustion performance was studied on the view of chemical kinetics. The discharge products were obtained by using the numerical simulation method in refs [8]. H atom, O atom and OH radical were added to the combustion flow field as major products of discharge, which are main factors effecting on the combustion process.

2. Models and Methods

2.1 PAC Rocket Engine Design.

Fig.1 displays the scheme of GH_2/GO_2 single co-axial injector rocket engine, gas O_2 is injected into chamber along the axial and GH_2 on its periphery. High voltage electrode is located in the axis, the surface is lay dielectric barrier layer, the length is 15 mm, and the diameter is 1mm. The ground electrode is located at the wall and has a length of 5 mm. The discharge area is located in the gas mixing zone between the high voltage electrode and the ground electrode, and the other areas of the wall are insulated.

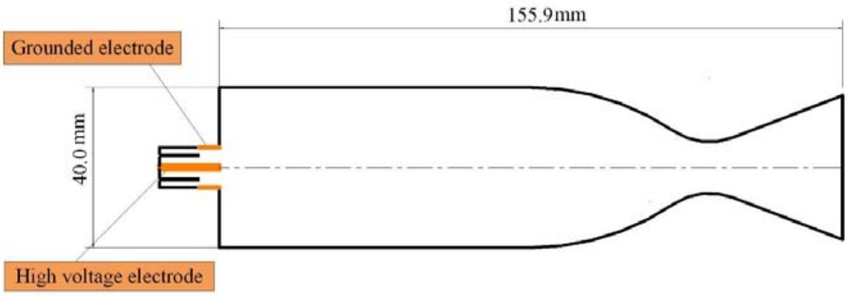


Fig. 1 The scheme of PAC rocker engine

2.2 Calculate Regions and Meshes.

Due to the coaxial injector and combustion chamber are axially symmetric, a two-dimensional axisymmetric model is used in calculation. So as to fully reflect the mixing and combustion characteristics, the injector to throat zone is taken as calculation area. Structural meshes are adopted in the whole computational domain, the number of mesh cells is 110,000.

2.3 Physical Models.

The control equations used in the calculation are the Reynolds-averaged, conservation and unsteady N-S equations with multi-component and chemical reactions. The turbulence model is the $k-\varepsilon$ standard model.

The combustion model uses Eddy Dissipation Concept (EDC) model that reflects the detailed chemical reaction mechanism in turbulent flow. The hydrogen-oxygen finite rate chemical reactions with 6 species and 7 reactions [9] used in EDC modle is shown in Table 1.

Table 1. Reaction set and rate coefficient

No.	Reaction	A_r((mol/cm^3)$^{1-m}$s^{-1})	β_r	E_r(kJ/mol)
1	$H_2+O_2 \longleftrightarrow OH+OH$	1.7×10^{13}	0	201.5
2	$H+O_2 \longleftrightarrow OH+O$	1.42×10^{14}	0	68.62
3	$H_2+OH \longleftrightarrow H_2O+H$	3.16×10^{7}	1.8	12.68
4	$H_2+O \longleftrightarrow OH+H$	2.07×10^{14}	0	57.53
5	$OH+OH \longleftrightarrow H_2O+O$	5.5×10^{13}	0	29.29
6	$H+OH+M \longleftrightarrow H_2O+M$	2.21×10^{22}	-2.0	0
7	$H+H+M \longleftrightarrow H_2+M$	6.53×10^{13}	-1.0	0

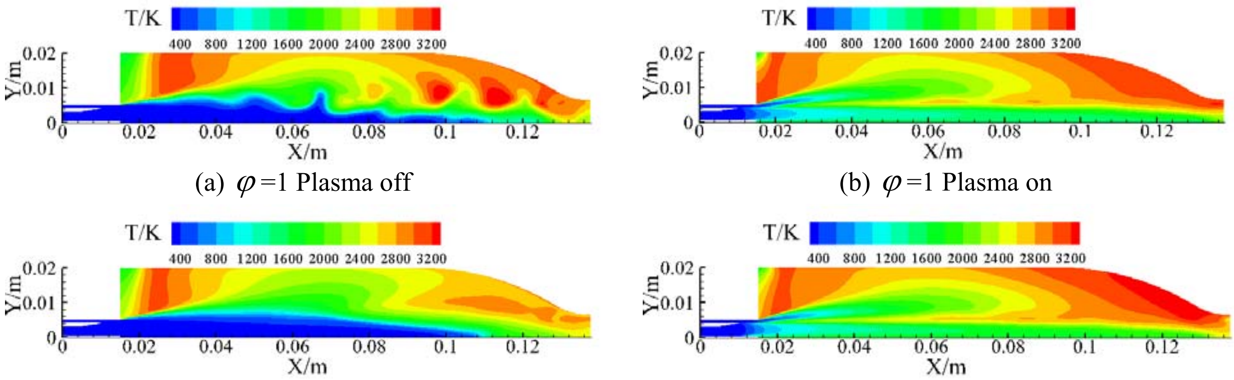
Hydrogen and oxygen inlet conditions are the mass flow inlet boundary, the outlet condition of combustion chamber is pressure outlet, the turbulent kinetic energy and the turbulent dissipation rate of the inlet and outlet are obtained according to the empirical formula, and the wall condition is no-slip and thermal isolation. Table 2 shows the gas mass flow rate in two operating conditions.

Table 2. Mass flow rate in two operating conditions

NO.	GH2 mass flow rate	GO2 mass flow rate	Equivalence Ratio
1	1.25g/s	10g/s	1
2	1.25g/s	8g/s	1.25

3. Result and Discussion

Figure 2 shows the temperature distribution of the flow field before and after the application of the plasma, and the flame structure of the combustion chamber is similar to the result in refs [10]. It can be seen that the axial temperature of the combustion chamber is significantly improved after the application of the plasma, and the overall temperature distribution in the combustion chamber is more uniform than when the plasma is not applied, in two operating conditions.

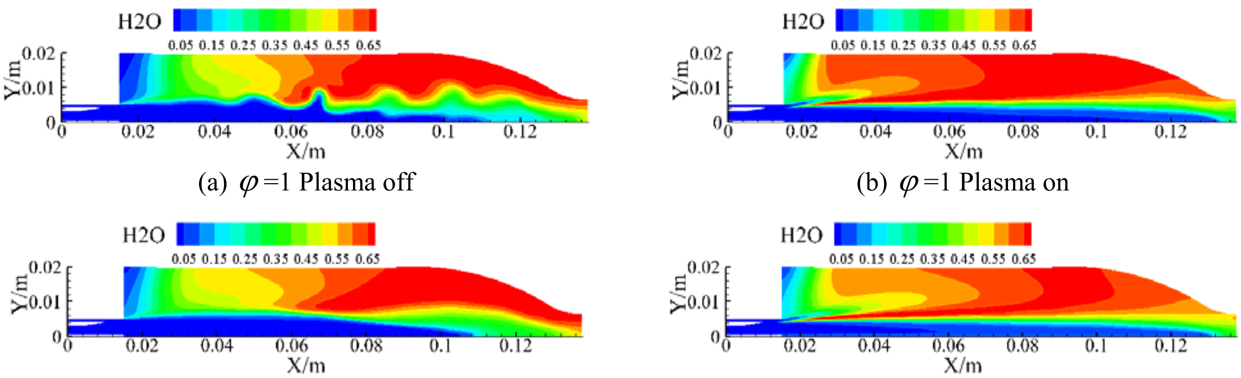


(a) φ=1 Plasma off (b) φ=1 Plasma on

(c) φ=1.25 Plasma off (d) φ=1.25 Plasma on

Fig. 2 Temperature contours with plasma on and off in two operating conditions

Figure 3 shows the distribution of the mass fraction of H_2O in the flow field before and after the application of plasma. It can be seen that the reaction product H_2O mainly concentrated in the middle and downstream area in combustion chamber before the application of plasma, after the application of plasma H_2O component concentration in combustion chamber head area increased significantly.



(a) φ=1 Plasma off (b) φ=1 Plasma on

(c) φ=1.25 Plasma off (d) φ=1.25 Plasma on

Fig. 3 Mass fraction of H_2O with plasma on and off in two operating conditions

When the plasma is not applied, the gas mixing effect of the combustion chamber head range is poor, the chemical reaction rate is low, and the combustion reaction is mainly concentrated in the downstream part of the combustion chamber where the gas is fully blended. Due to the presence of active particles, the chemical reaction of the combustion chamber is obviously accelerated, and the effect of the exothermic effect of the reaction can further enhance the gas blending performance, thus improving the combustion efficiency of the whole combustion chamber.

4. Conclusion

In this paper, the non-equilibrium plasma combustion-assisted configuration of the spacecraft rocket engine is designed. The influence of the plasma on the combustion performance of the engine is studied from the point of view of chemical kinetics. The results show:

(1) Non-equilibrium plasma can expand the flame range in the combustion chamber, the combustion chamber axial temperature increased significantly.

(2) The rate of chemical reaction in the head region of the combustion chamber is significantly increased after the application of the plasma, and the exothermic effect contributes to the hydrogen and oxygen blending performance and then promote the combustion efficiency in the chamber.

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