The role of non-equilibrium plasma kinetic effect on GCH4/GOX rocket engine combustion performance

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Abstract. Non-equilibrium plasma has significant chemical kinetic effect and aerodynamic effect, both of which play an important role in the plasma-assisted combustion. In this paper, the numerical study on plasma-assisted combustion in gaseous methane rocket engine is carried out to investigate the impact of kinetic effect on its combustion performance. There are three schemes of plasma excitation via oxygen, methane and both of them in the numerical simulation model. The variations of combustion chamber temperature, pressure, species concentration and special impulse with different dissociation degrees are analysed in three discharge schemes. The results show that non-equilibrium plasma can effectively increase methane burning rate, shorten unburnt area upstream of combustion chamber, and increase the width of combustion zone in shear layer upstream of combustion chamber. And this phenomenon becomes more obvious with the increase of excitation intensity. In addition, more methane and oxygen are added to the combustion process under plasma actuation, and the mole fraction of water is increased in combustion products. The specific impulse of engine is also increased under plasma actuation. At the same degree of dissociation, the combustion-supporting effect of simultaneous discharge of oxygen and methane is significantly greater than that of any component discharge. And in the condition of single component discharge, the combustion-supporting effect of methane is better than that of oxygen.

1. Introduction
Methane is one kind of the propellants which is green, non-toxic and low-cost. It has great application potential in reusable engine, variable thrust engine and low-thrust engine in space propulsion system. Most of these engines work in the extremely severe environment of low temperature and high vacuum for a long time, which requires multi-time or pulse ignition and a wide range of variable thrust. Therefore, the CH₄/O₂ rocket engines are faced with many key technical challenges in achieving reliable repetitive ignition [1], stable combustion [2] and high combustion efficiency.

Non-equilibrium plasma assisted combustion (PAC) not only can effectively improve ignition reliability, enhance combustion stability, shorten ignition delay, but also can broaden flammable limits and improve combustion efficiency [3-6], which provides a new technical way to solve the difficulties of reliable ignition, efficient and stable combustion and performance optimization for CH₄/O₂ rocket engine. In the paper [7] CEA program is used to analyse the combustion-supporting effect of O and N components in octane combustion process. The results show that the plasma can increase the active intermediates in the reaction process of rocket engine, and improve the reaction rate and averaged combustion chamber temperature. Based on the kinetic effect of plasma species, active particles of
different propellants under discharge is added to initial reaction components for H2/O2 rocket engine in Ref [8], the results show that the active particles can effectively improve the chamber pressure and specific impulse of the engine.

Non-equilibrium plasma controls the combustion flow field mainly based on its chemical kinetic effect and aerodynamic effect, in which the aerodynamic effect can enhance the jet instability and improve the fuel mixing efficiency, and the activation effect can change the reaction path and increase the reaction rate in combustion dynamics. However, up to now it is difficult to decouple the two effects and make single effect applied to flame in experiment, to analyze the control effect and mechanism of each effect on combustion. Through numerical simulation method the kinetic effect of plasma can be simulated and used to control combustion, that make up for the shortcomings of the experimental methods at present. For this reason, the influence of plasma kinetic effect on rocket engine combustion performance is studied by numerical simulation method in the paper. In details, the effects of O, CH3 and H additions on combustion chamber temperature, pressure, combustion products and specific impulse are analysed under three schemes: oxygen discharge, methane discharge and both of them discharge.

2. Numerical simulation model

The model of CH4/O2 rocket engine developed in simulation research of Munich University is used as the engine model in this paper [9], and its size parameters are shown in table 1. The engine adopts a single coaxial shear gas injection unit. The temperature of oxygen injection in inner nozzle and methane injection in outer nozzle is 278k and 269k, respectively. And mass flow rate is 45g/s and 17g/s. The working pressure of combustion chamber is 2MPa. The combustion reaction mechanism is described in Ref. [10], including 14 components and 18 steps of reaction formulas.

| Table 1. The geometrical parameters of combustor |
|-----------------------------------------------|
| Combustion chamber length $l$ [mm]            | 290  |
| Combustion chamber diameter $Dc$ [mm]         | 13.5 |
| Contract ratio $A_{cc}/A_{ih}$ [ -- ]         | 2.5  |
| Inner nozzle diameter $D_i$ [mm]              | 4    |
| Retraction distance of inner nozzle [mm]      | 0    |
| Wall thickness of inner nozzle $w$ [mm]       | 0.5  |
| Outer diameter of outer nozzle $D_e$ [mm]     | 6    |

In the early stage, the research team has carried out the establishment of numerical calculation model and verified the accuracy of the model calculation results [11]. The research content of this paper is to further expand more discharge schemes and analyse the influence of plasma kinetic effect on combustion performance of rocket engine. The discharge cases based on dissociation degree is divided into four working conditions, as shown in table 2. Besides oxygen dissociation, the influence of methane dissociation, methane and oxygen dissociation on combustion are also considered in each dissociation condition. The discharge conditions of different dissociation degrees from 0.8% to 5% are represented by Case1 to Case4. And the discharge schemes of oxygen, methane, and both of them at the same dissociation degree are represented by A, B and C.

| Table 2. The dissociation degree of propellant in different cases (oxygen-A; methane-B; oxygen and methane-C) |
|---------------------------------------------------------------------------------------------------------------|
|                                                                                                               |
| Case1 | Case2 | Case3 | Case4 |
| Dissociation degree | 0.08% | 1% | 0.3% | 5% |
3. The combustion performance of rocket engine

3.1. Temperature and pressure of combustor

Figure 1 shows the temperature distribution of combustor in centre section under Case4-A. It can be seen that under oxygen discharge, the combustor temperature distribution remains the same compared with no plasma, and it need to further analyse the change of combustion flow field from a detail perspective.

![Figure 1. Temperature distribution with oxygen discharge](image)

Figure 2 shows the temperature distribution of the white dotted box area in figure 1(a), with the $x$ range of 180–200mm and $y$ range of -3–3mm. Taking the isopleth at temperature $T = 2500K$ as a reference, the rightmost end of the isopleth moves upstream along the axis with plasma, and Case2-A moves 0.3mm relative to no discharge. When the discharge intensity is further increased to Case 5-A, the rightmost end of the isopleth moves 3.7mm upstream relative to the no discharge, which is about 1.94% of the length of the chamber. It reveals that the kinetic effect of oxygen discharge can effectively promote the methane combustion upstream along the axial direction, shorten the unburned area upstream of combustor, and this phenomenon becomes more obvious with the increase of excitation intensity.

![Figure 2. Local temperature distribution with oxygen discharge](image)

In order to analyse the influence of plasma on the shear combustion layer on both sides of the upstream central line of the combustion chamber, the temperature distribution curves along $y$-axis under different working conditions were obtained at $x = 30, 60$ and 90mm, as shown in figure 3. It can be seen that the plasma does not change the peak value of the shear layer temperature, but mainly affects both sides of the temperature peak value significantly. Corresponding to $x = 30mm$, it can be seen from figure 3(a) that the value of the right side of the curve is somewhat increased with discharge. When the combustion shear layer develops to 60mm and 90mm of $x$-axis, the temperature on the left side of the curve also increases significantly after discharge. It indicates that the kinetic effect of
oxygen discharge can effectively enhance the combustion intensity of the shear layer and expand the combustion range of the shear layer, but it is first reflected in the outer side of the combustion shear layer, that is, the side close to the combustor wall.

In order to analyse the influence of plasma kinetic effect on engine performance under methane discharge, the temperature distribution of combustion chamber under Case4-B is given in figure 4. When the kinetic effect of methane discharge is applied to combustion process, the temperature field still remains unchanged compared with that without plasma, which is the same as that of oxygen discharge.

To analyse the effect of methane discharge on the upstream shear layer combustion, the longitudinal temperature distribution curves under different discharge conditions were also obtained at $x = 30, 60$ and $90$mm, as shown in figure 5. The temperature peak values of the curves in above cases are almost unchanged, which is the same as that of oxygen dissociation. It is worth noting that, methane discharge has no obvious effect on the left side of the temperature curves, but only on the right side.
Figure 6 reports the temperature distribution with oxygen and methane discharge in Case4-C. It can be seen that the combustor temperature distribution is same to that without plasma, which indicates that the scheme of oxygen and methane simultaneous discharge still has no obvious influence on combustion form of engine.

![Temperature distribution](image)

**Figure 6.** Temperature distribution under oxygen and methane discharge

Figure 7 shows the kinetic effect of oxygen and methane simultaneous discharge on shear layer combustion. In the discharge scheme of Case4-B there remains no obvious effect on the peak value of temperature profiles, which is the same as discharge scheme of each component dissociation. The temperature on both sides of peak value are significantly affected when they discharge at the same time. And the control effect seems to be superposition of each component discharge, because it is more obvious than single component discharge.

![Temperature profiles](image)

**Figure 7.** Temperature profiles under oxygen and methane discharge

In order to compare the influence of oxygen discharge, methane discharge and simultaneous discharge of oxygen and methane on combustor temperature ($T$) and chamber pressure ($P_c$), the increase amplitude of temperature profiles of central $x$-axis and central chamber pressure under different dissociation degrees of Case1 to Case4 are shown in figure 8. According to figure 8(a), it can be seen that under the same degree of dissociation, the scheme of simultaneous discharge of oxygen and methane shows the strongest effect, followed by methane discharge, and oxygen discharge in terms of improving the combustion chamber centre temperature, expanding the upstream combustion zone and enhancing the combustion intensity. It is worth noting that methane dissociation shows a stronger kinetic effect than oxygen dissociation in enhancing combustion.

Figure 8(b) shows that the increasing range of combustion chamber central pressure is significantly lower than that of central temperature. Due to the positive correlation between temperature and chamber pressure, the three control schemes have the same order of strength in improving chamber pressure as the central temperature.
3.2. Species concentration distribution

To investigate the influence of plasma kinetic effect on the species concentration distribution in combustor, the distribution of O$_2$, H$_2$O and CO$_2$ is reported in figure 9. Since the combustion flow field has the feature of central symmetry, only one side of the central section is shown in figure 9. In order to directly compare the changes of species distribution before and after discharge, the intersection points between the contour lines of the three species and the combustor wall or central axis are marked as Q1, Q2 and Q3 respectively when there is no plasma, and the white longitudinal dotted line is used as the reference line under different working conditions.

According to figure 9(a), when the plasma actuator is turned on under listed discharge schemes, compared with the case of no plasma, the contour lines of O$_2$ mole fraction move upstream in different degrees, which is consistent with the change trend of temperature field. It indicates that plasma kinetic effect can effectively increase methane burning rate and promote methane combustion. In addition, the effect of the three discharge schemes on O$_2$ concentration is the same as that on the temperature field, that is, the simultaneous discharge of oxygen and methane is the strongest, followed by methane and oxygen. It can be seen that under the plasma kinetic effect, the variation of O$_2$ concentration and the influence degree of different discharge schemes are consistent with the temperature field, which
indicates that the increase of combustor temperature is caused by combustion enhancement rather than the conversion of internal energy of chemical active particles into heat energy. It worth noting that the kinetic effect can effectively shorten the axial distribution length of $O_2$ injection, which provides a technical possibility for shortening the length of combustion chamber in engine design.

In figure 9(b)–(c), because $H_2O$ and $CO_2$ are combustion products, they are distributed in the combustion area of the combustor. According to the change of $Q2$ and $Q3$, the distribution zones of $Q2$ and $Q3$ expand to the upstream under three discharge schemes, which is consistent with the variation of $O_2$ after discharge. According to the change of $Q1$ point, the distribution area of $CO_2$ and $H_2O$ near the nozzle outlet expands upstream to the backstep with methane discharge, which indicates that the plasma can also expand the combustion area near the nozzle and make the combustion zone close to the injection panel.

### 3.3. Specific impulse of rocket engine

Figure 10 shows the change of the specific impulse ($I_{sp}$) and its increase amplitude in different cases. It can be seen that under different control schemes, the plasma kinetic effect can effectively increase the engine specific impulse by enhancing the engine combustion, and the control effect becomes stronger with the increase of excitation intensity. Under the same dissociation degree, the increase of specific impulse with oxygen and methane discharge is significantly greater than that of single component discharge. And in the condition of single component discharge, the increase of methane discharge is better than that of oxygen discharge.

![Figure 10. Engine specific impulse under different cases](image)

### 4. Conclusion

In this paper, the kinetic effect of non-equilibrium plasma on rocket engine combustion performance, including chamber temperature, chamber pressure, composition and specific impulse was analysed. The results show:

1. Non-equilibrium plasma can effectively promote the methane combustion upstream, shorten the unburnt area in the upstream of the combustor and expand the combustion area downstream, and the effect is gradually enhanced with the increase of excitation intensity.

2. Non-equilibrium plasma can effectively increase the width of combustion zone in shear layer upstream of combustion chamber. In addition, more methane and oxygen are added to the combustion process under plasma actuation, and the mole fraction of water is increased in combustion products.

3. Specific impulse of the rocket engine is increased under plasma-assisted combustion, and the increase of simultaneous discharge of oxygen and methane is significantly greater than that of any component discharge.
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