Numerical study of plasma assisted combustion for a rocket combustor using GCH4/GOX as propellants

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Abstract. In order to study the effect of active particles in plasma on the combustion of small rocket engines, the combustion characteristics of the combustion chamber under different ionization levels of fuel and oxidant were simulated. The results show that with the increase of the ionization degree of fuel and oxidant, the high temperature region of the combustion chamber advances and the proportion increases; the pressure of the combustion chamber increases continuously, so as to achieve the effect of increasing the engine thrust. It shows that the ionized active particles can shorten the propellant ignition delay, improve the combustion efficiency of the engine combustion chamber, making the combustion more fully; increase the combustion chamber pressure so as to increase the engine specific impulse.

1. Introduction
The spacecraft power system is of great significance to the aerospace industry. The development of aerospace projects such as manned space flight, lunar exploration and deep space exploration in China all rely on rocket power. The small-thrust rocket engine has a very wide range of applications on satellites, space shuttles, upper stage of multi-stage vehicles and other spacecraft’s [1]. It is mainly used for tasks such as orbit control, attitude control and space landing et al. Most domestic and foreign spacecraft, such as rockets and satellites, currently use nitro-oxidants and thorium fuels as propellants. Although these propellants have good performance and mature technology, they are highly toxic, expensive and pollute the environment. They cannot adapt to the human space mission needs in the future.

With the rapid development of manned spaceflight, the non-toxic propellants have become an inevitable trend of development [2-3]. Methane fuel is a good choice for non-toxic propellants because of its high specific impulse, low cost, and low pollution. However, when it is used as an orbit control or attitude control engine, it is faced with problems such as difficulty of ignition under low temperature and high vacuum conditions. Spacecraft attitude and orbit control rocket engine has less injection unit so propellant mixing efficiency is low, the combustion chamber volume is small, so combustion time for propellant is short, which is not conducive to the full combustion of the propellant [4]. Spacecraft rocket engines should have a strong ability to change thrust to meet the needs of different working conditions. When the thrust is adjusted by changing the propellant flow rate and mixing ratio, the engine is prone to occur combustion instability, which will lead to lower combustion efficiency or even damage the engine. Advanced technical urgently need to be adopted to ensure the efficient and stable combustion of the engine under various working conditions [5].
As the plasma has the potential to improve the combustion efficiency, expand the flammability, and stabilize the combustion flame under severe working conditions, the plasma assisted ignition and plasma assisted combustion have received extensive attention [6-7]. At present, researchers have summarized the mechanism of plasma combustion into the following aspects: thermal effects, chemical kinetic effects, and transport effects [8-9]. Applying plasma technology to spacecraft rocket engines, researching plasma assisted ignition and plasma assisted combustion for spacecraft rocket engine special working environment and performance requirements can promote the development of China's spacecraft rocket engine technology, supporting for China's major space projects such as manned spaceflight and deep space exploration et al.

In this paper, the combustion chamber of a gas-oxygen/gas-methane coaxial single nozzle rocket engine is constructed. The effects of different degrees of ionization of fuel and oxidant on the combustion characteristics of the rocket engine combustion chamber are studied. The relevant results can provide some reference for the future research of plasma assisted combustion for small thrust rocket engines.

2. Numerical simulation approach

2.1. Simulation object and numerical methods
The rocket engine chamber designed by Technical University of Munich, Institute for Turbo machinery and Flight Propulsion, Germany is adopted as simulation object [10]. Relevant parameters are shown in Table 1.

| Parameter                        | Value  | Parameter                        | Value  |
|----------------------------------|--------|----------------------------------|--------|
| Nominal chamber pressure (Bar)   | 20.0   | Chamber diameter (mm)            | 12.0   |
| Fuel mass flow (g/s)             | 13.5   | GO₂ diameter (mm)                | 4.0    |
| Oxidant mass flow (g/s)          | 35.1   | GO₂ post thickness (mm)          | 0.5    |
| Fuel inlet temperature (K)       | 269    | GCH₄ outer diameter (mm)         | 6.0    |
| Oxidant inlet temperature (K)    | 275    | Throat diameter (mm)             | 7.6    |
| Chamber length (mm)              | 305.0  | Contraction ratio                | 2.5    |

The engine uses a gaseous propellant, so it does not need to consider evaporation and atomization during combustion, only the mixing and chemical reaction process is considered. In the simulation process, the models involved are turbulence model, chemical kinetic model, and turbulence-chemical reaction interaction model. For the simulation the Reynolds-averaged Navies-Stokes (RANS) equations were solved, turbulence is modeled using a standard k-ε model and the wall is treated using standard wall Fn. The combustion is modeled using a laminar finite rate chemistry model, i.e. turbulence chemistry interaction (TCI) is neglected. As chemical kinetic scheme a 14 species 18 reaction reduced mechanism [11] is used.

2.2. Computational zone, initial and boundary conditions
The engine is symmetrical and the computational domain contains the injector, chamber, and nozzle. In order to reduce the calculated amount, it can be simplified as a two-dimensional axisymmetric structure. The structural grid was used to divide the computational domain and the nozzles and walls were encrypted. As shown in Figure 1, the total number of grids was about 71000.

The finite volume method is used to discrete control equations. For the nonlinear mutual coupling characteristic of N-S equations, the pressure and velocity decoupling are implemented using the pressure implicit operator splitting algorithm (PISO). The convection terms are discretized using the second-order upwind scheme, and the viscous terms are discretized using the central difference
scheme. At the inlet the mass flow rates are given together with injection temperature as listed in Table 1. The outlet is set to a pressure outlet.

![Computational zone and meshing](image)

**Figure 1.** Computational zone and meshing

### 2.3. Model validation

The Technical University of Munich, Germany, has conducted experiments and numerical simulations on this engine under various conditions. The relevant data from the literature can provide verification for the simulation model in this paper. Figure 2 shows the comparison between the temperature field obtained by simulation in this paper and the temperature field in [10]. It can be seen from the figure that the temperature distributions of the two pictures are basically the same. Figure 3 shows the comparison of the wall pressure distribution of the combustion chamber simulated in this paper with the experimentally measured under the same conditions in [10]. It can be seen from the figure that the wall pressure distribution of the combustion chamber obtained by simulation agrees well with the experimental values. In summary, we can verify the correctness of this simulation model.

![Temperature field comparison](image)

**Figure 2.** Calculated temperature field vs temperature field in the literature

![Wall pressure comparison](image)

**Figure 3.** Wall pressure from CFD simulation vs experiment
3. Results and analysis

To study the combustion-supporting effect of non-equilibrium plasma in rocket engines, it is assumed that when the propellant is injected into the combustion chamber, the gas is processed by the plasma exciter. The fuel and oxidant of different ionization levels were added to the combustion flow field as the initial component, and a total of five conditions were included, as shown in Table 2.

Table 2. Ionization Degree under Different Operating Conditions

|        | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 |
|--------|--------|--------|--------|--------|--------|
| CH₄    | 0      | 5‰     | 0      | 5‰     | 10‰    |
| O₂     | 0      | 0      | 5‰     | 5‰     | 10‰    |

3.1. Influence of plasma on the temperature distribution of the combustion chamber

Figure 4 shows the change of the center temperature of the combustion chamber along the axial direction under different working conditions. It can be seen from the figure that the temperatures in different conditions are basically the same in the front and rear sections of the combustion chamber, in the middle section of the combustion chamber, and in the reference state. Compared with Case 1, Case 2 to Case 5 all accelerated the temperature increase to different extents, that is, the distance to the same temperature was shortened, indicating that the active particles produced by ionization increased the propellant combustion efficiency. It can be seen from the figure that under the same degree of ionization, ionized CH₄ has a greater effect on combustion than ionized O₂.

Figure 4. Temperature distribution along axis direction under different conditions.

Figure 5 compares the temperature fields of Case 1 and Case 5. It can be seen from the figure that the Case 5 high temperature zone is closer to the front of the combustion chamber and the range is larger than Case 1. It shows that the injection of propellant into the combustion chamber under the condition of Case 5 can achieve faster ignition and combustion, and the addition of active particles shortens the ignition delay, so that the propellant burns more fully under the same volume combustion chamber conditions.

Figure 5. Comparison of temperature distribution.
3.2. Influence of plasma on combustion chamber pressure
Combustion chamber pressure is an important index to measure engine performance. The combustion chamber pressure under different operating conditions is shown in Figure 6. Figure 6 a) shows the change of the wall pressure of the combustion chamber under different working conditions. It can be seen from the figure that the addition of active particles generated by ionization increases the wall pressure of the entire combustion chamber. Under the same degree of ionization, the effect of increasing the wall pressure of the combustion chamber obtained by the ionized fuel and the oxidant is not much different. The effect of ionized O2 is slightly better than that of the ionized CH4. Figure 6 b) shows the change of the combustion chamber pressure under different working conditions. It can be seen that the addition of active particles generated by ionization can increase the pressure of the combustion chamber, and the greater the degree of ionization, the more obvious the effect.

![Graphs showing combustion chamber pressure](image)

**Figure 6.** Chamber pressure under different conditions.

4. Conclusion
In this paper, the impact of different ionization conditions of fuel and oxidant on engine combustion is studied for a small-thrust oxygen/gas methane rocket engine. The main conclusions are as follows:

1. The active particles produced by ionization can shorten the ignition delay of the propellant and allow the propellant to achieve more complete combustion under the same volume of the combustion chamber.
2. The addition of active particles produced by ionization can increase the pressure in the combustion chamber, and the greater the degree of ionization, the more obvious the effect.
3. Under the same degree of ionization, the effect of ionized oxidant on the combustion chamber pressure is slightly better than that of ionized fuel, and the effect of ionized fuel on temperature is more pronounced than that of ionized oxidant.

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