Numerical Simulation of Plasma Jet Assisted Combustion Based on the Strut Combustor

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Abstract. Inserting a fuel injection strut into the combustor of the scramjet engine or injecting plasma jet into the combustor are two proven effective ignition and combustion assistance aids. Based on this, a strut with Alternating-Wedge structure capable of simultaneously injecting fuel and plasma jet is designed and numerical simulation is carried out. The numerical simulation results show that the fuel injected from the side of the strut is affected by the Alternate-Wedge structure, the distribution in the downstream is wider, and distribution of the fuel shows a clear streamwise vortices structure; Different plasma jet medium have different combustion-assisted effects. The effect of combustion-assisted is positively correlated with the concentration of O2 in the jet medium; increasing the temperature of the plasma jet can improve the combustion efficiency of the combustor within a certain range.

1. Introduction
In the combustor of scramjet engine, the fuel stays for a very short time [1]. In order to achieve sufficient mixing and combustion of fuel and air in such a short period of time [2], the researchers insert a strut capable of injecting fuel into the center of the combustor. The strut injector changes the flow field structure to promote the mixing of fuel air [3]. Among them, the Alternating-Wedge strut can form reverse streamwise vortices pair, further promoting the mixing of fuel and air, and is a widely used injector structure [4].

Another approach is to use plasma for ignition and combustion assistance. Plasma jet is one of them, which assists ignition and combustion by generating a high-speed, high-temperature plasma jet. The plasma jet mainly achieves combustion assistance through three ways: thermal effect, aerodynamic effect and chemical effect. First, the high-temperature plasma jet can release a large amount of energy, which helps to quickly ignite the fuel; secondly, the plasma jet can change the flow field to some extent, further improving the fuel distribution; finally, the active particles contained in the plasma jet can accelerate the reaction rate and promote combustion.

As early as 1981, Kimura first applied plasma jet to the ignition and combustion assistance of hydrocarbon fuels in supersonic flow [5]. Subsequently, the researchers conducted extensive research on plasma jet assisted ignition and combustion in supersonic flow. In 2003, Murakami contrasted the combustion assistance effects of different plasma jet medium [6]. In 2005, Minato studied the O2 plasma jet assisted ignition and combustion by numerical simulation [7]. By comparing the reaction product and the temperature distribution of the combustor, it was found that the combustion efficiency
showed an increasing tendency as the plasma temperature was higher. Takita conducted an ignition experiment of a double plasma jet in supersonic flow [8].

Domestically, Wei Baoxi simplified the plasma jet to high-temperature jet by numerical simulation, and analyzed the combustion efficiency of the fuel [9]. Duān Liwei focused on the effect of plasma jet on supersonic combustion [10], and found that the combustion promotion effect of plasma jet is considerable; Song Zhenxing simplified the plasma jet to an oxygen jet with an ionization degree of 0.5%. The numerical simulation results show that the effect of high temperature plasma improves the ignition efficiency of hydrogen; Liu Yi [11] studied plasma jet assisted ignition and combustion characteristics through a combination of experiments and numerical simulations.

However, most of the current researches on plasma jet use wall injection methods such as transverse jet flow, which have certain limitations on the distribution range of fuel. Therefore, this paper proposes a method of combining strut injection and plasma jet to promote combustion in supersonic combustor.

2. Numerical methods and models

2.1. Combustor models

The combustor structure selected in this paper is divided into isolation section, combustion section and expansion section. In order to improve the calculation efficiency, this paper focuses on the numerical simulation of the combustion section.

![Figure 1. Structure of the combustion section](image)

The structure of the combustion section of the combustor is shown in Figure 1. The length is 450 mm, the width is 70 mm, the inlet height is 51 mm, the upper and lower walls have an expansion angle of 2°, and the tail of the strut is 110 mm from the inlet of the combustion section.

Figure 2 is a structural diagram of the strut. The compression angle at the leading edge of the strut is 15°, the length of the strut is 100mm, the width is 70mm, and the thickness is 10mm. The expansion angle at the tail of the strut is 27°. Six fuel injection holes are arranged at equal intervals on the side of the strut. The center of the injection hole is 30mm from the tail of the strut, the radius of the injection hole is 2mm, the plasma jet injection holes are arranged at equal intervals at the tail of the strut, and the radius of the injection hole is also 2mm.
2.2. Numerical methods
The numerical simulation of this paper adopts the RANS numerical method, the continuous phase turbulence model is selected as the $k-\omega$ SST model, and the density-based implicit solver is used to solve the steady state problem.

(1) Inlet conditions: The pressure far-field boundary conditions are adopted, given the Mach number, static pressure, static temperature and mass fraction of each component;

(2) Outlet conditions: The pressure outlet boundary conditions are adopted;

(3) Fuel inlet conditions: The pressure inlet boundary conditions are adopted, given the total pressure, static pressure, total temperature and mass fraction of each component;

(4) Plasma jet inlet conditions: The pressure inlet boundary conditions are adopted. Minato's research shows that in the plasma jet used in supersonic combustors, the types and quantities of active particles are small, and the impact on combustion efficiency is limited. The decisive effect of combustion efficiency is the high temperature of the plasma jet. Therefore, in this study, the plasma jet is simplified to high temperature jet for numerical simulation.

(5) Wall conditions: The adiabatic and non-slip wall boundary conditions are adopted.

Table 1. Different inflow parameters

|       | Mach number | Total pressure | Static pressure | Total temperature | Static temperature |
|-------|-------------|----------------|-----------------|------------------|-------------------|
| Cold  | 2.7         | 530KPa         | 30KPa           | 308K             | 125K              |
| Hot   | 3           | 2.11MPa        | 50KPa           | 1650K            | 702K              |

The inflow parameters of the combustor under different conditions are shown in Table.1. The fuel selected is $\text{H}_2$, the total injection pressure is 2.0 MPa, and the total temperature is 308K. The plasma jet is simplified to high temperature gas jet with a total injection pressure of 1.0 MPa.

3. Results and analysis

3.1. Flow field analysis of strut combustor

Figure 3. Contours of Static pressure in section Z=0mm
Figure 3 is the contours of static pressure in section Z=0mm of cold flow field with only fuel injection. The main features of the cold flow field are the oblique shock wave 1 generated at the head of the strut; the reflected shock wave 2 formed by the reflection of the oblique shock wave 1 and the wall surface; and the expansion wave 3 at the tail of the strut; there are also oblique shock waves 4 formed by the fuel injection; and a reflected shock wave 5 formed by the reflection of the wall and oblique shock wave 4, These shock waves constantly reflect and intersect to propagate downstream.

Figure 4. Contours of mole fraction of H$_2$ in section Z=0mm

Figure 4 is the contours of H$_2$ mole fraction on the center section of the combustor. After H$_2$ is injected from the injection hole on the side of the strut, it is distributed along the surface of the strut due to the effect of high-pressure flow, and then the fuel enters the tail of the strut. Due to the effect of the streamwise vortices, fuel diffuses from the center of the strut to both sides along the direction of the flow.

Figure 5. Contours of mole fraction of H$_2$ in different sections

Figure 5 is the contours of mole fraction of H$_2$ in different sections along the inflow direction, in which the streamwise vortices structure induced by the Alternating-Wedge structure can be clearly seen. The presence of such a streamwise vortices structure effectively promotes the downstream diffusion of H$_2$.

Figure 6. Contours of combustion flow field without plasma jet
(a) mole fraction of H$_2$O; (b) static temperature
In order to compare the effect of plasma jet on the combustion performance of the combustor, the combustion flow field without plasma jet was first analyzed. Figure 6 is the contours of mole fraction of H$_2$O and static temperature when no plasma jet is added. The distribution of H$_2$O is basically consistent with the high temperature region in Fig.6 (b), and the region where the combustion occurs is also consistent with the distribution of H$_2$ in Fig. 4. When there is no plasma jet injection, the area immediately behind the strut and the outermost area of the downstream hydrogen distribution range are the main areas where combustion occurs.

3.2. Influence of different plasma medium on combustion performance

![Figure 7. Contours of mole fraction of H$_2$O under different plasma medium (a) N$_2$; (b) air; (c) O$_2$](image)

In order to study the effect of different plasma jets on combustion assistance, three different plasma jet medium of N$_2$, Air and O$_2$ were selected for numerical simulation. The temperature of plasma jet is 3000K.

Figure 7 is the contours of mole fraction of H$_2$O under different plasma medium. It can be seen that the concentration of the H$_2$O changes significantly after the addition of the plasma jet. Comparing the H$_2$O distribution under different plasma jet medium, the results show that selecting N$_2$ as the medium has the worst combustion assistance effect.

When N$_2$ is used as the plasma jet medium, the concentration of H$_2$O is even lower than that without plasma jet. This is because the concentration of air is diluted to some extent after N$_2$ injection behind the strut, thus causing the combustion efficiency in the near field region is lowered.

When air and O$_2$ are used as the plasma jet medium, the combustion assistance effect is better. Especially when O$_2$ is used as the plasma jet medium, the concentration of H$_2$O in the combustor increases obviously, indicating that O$_2$ is the best plasma for the combustion assistance.

This also shows that the concentration of O$_2$ in the plasma jet medium is an important factor in the combustion assistance effect.
Figure 8. Contours of static temperature under different plasma medium (a) N$_2$; (b) air; (c) O$_2$

Figure 8 is the contours of static temperature under different plasma medium, the high temperature region in the figure coincides with the distribution of the mole fraction of H$_2$O in figure 7, which also indicates that the high temperature region is indeed produced by the combustion of the fuel.

From the contours of mole fraction of H$_2$O and static temperature of combustor, the influence of different jet media on combustion can be qualitatively seen. The introduction of combustion efficiency can quantitatively describe the effect of different jet media on combustion.

Combustion efficiency is an important parameter related to the combustor, which directly affects the performance of the scramjet engine. Its calculation formula is as follows:

$$\eta_c = 1 - \int_A p u C_{H_2} dA$$

$$M_{H_2}$$ is the total mass flow of H$_2$.

Figure 9. Combustion efficiency under different plasma jet medium
Figure 9 shows the combustion efficiency of the combustor under different plasma jet medium. Coordinate origin is 10 mm from the tail of the strut. As can be seen from figure 9, the high temperature plasma injected into the flow at the tail of the strut significantly improves the combustion efficiency of the combustor. Moreover, the combustion assistance effects of different plasma medium are quite different. When the plasma jet medium is N₂, although the high temperature effect of the plasma jet contributes to the ignition and combustion, since the plasma jet medium contains a large amount of N₂, the concentration of O₂ in the combustor is lowered, so the combustion efficiency at some sections is even lower than when no plasma jet is added.

When the plasma jet medium is air and O₂, the combustion efficiency of the combustor is improved to different degrees.

In particular, when the plasma jet medium is O₂, the combustion efficiency at the exit of the combustion section is increased by 1.35 times compared with when no plasma is added. Moreover, the combustion efficiency still shows a significant increase trend. As the combustor continues to expand, the combustion efficiency will further increase.

3.3. Influence of different plasma temperature on combustion performance

The temperature is also an important factor affecting the combustion assistance effect of the plasma jet. In order to verify the effect of plasma jet temperature on the plasma combustion assistance effect, the plasma jet with total temperature of 2500K, 3000K, and 3500K were selected for numerical simulation, the plasma jet medium was selected as O₂.

When comparing the effects of different jet temperatures on the combustion performance of the combustor, the temperature distribution through the combustor cannot accurately reflect the area where the combustion occurs, which is easily confused with the temperature of the jet itself. Therefore, the area where combustion occurs is determined by comparing the distribution of the combustion product H₂O in different cases.

Figure 10. Contours of mole fraction of H₂O under different plasma temperature (a) 2500K; (b) 3000K; (c) 3500K

Figure 10 is the contours of mole fraction of H₂O under different plasma temperature. Comparing the H₂O distribution on the center section of the combustor, it can be seen that as the plasma jet temperature increases, the concentration of H₂O also shows a certain increase trend. when the
temperature rises to 3500K, almost all of the mole fraction of H₂O in the center section of the combustor reached 0.3 or more. This is the result of the thermal effect of different temperature plasma jet.

![Combustion efficiency of the combustor at different plasma jet temperatures](image)

**Figure 11.** Combustion efficiency of the combustor at different plasma jet temperatures

Figure 11 shows the combustion efficiency of the combustor at different plasma jet temperatures, where T = 0K indicates that there is no plasma jet injection. It can be seen that within the range of 2500K-3500K, as the temperature of the plasma jet increases, the combustion efficiency also shows a significant increase trend. When the jet temperature rises to 3500K, the combustion efficiency reaches 54% at the exit of the combustor and shows a rapid growth trend. Therefore, the combustion efficiency at the exit of the combustor will be significantly improved.

4. Conclusion

In this paper, an Alternating-Wedge structural strut is designed, which combines fuel injection and plasma jet injection. The combination of streamwise vortices and plasma jet is used to promote combustion in the combustor. The following conclusions were obtained through numerical studies.

1. The fuel injected from the side of the strut is affected by the Alternating-Wedge structure of the tail of the strut. Along the direction of the flow, the fuel diffuses from the center of the strut to both sides and exhibits a distinct streamwise vortices structure;

2. Injecting plasma jet at the end of the strut can effectively improve the combustion efficiency of the combustor, and the influence of different plasma medium on the combustion of the combustor is different; the combustion assistance effect of the plasma jet is positively correlated with the O₂ concentration in the plasma jet;

3. The plasma jet temperature is also an important factor affecting the plasma combustion assistance effect. Increasing the plasma jet temperature within a certain range increases the combustion efficiency of the combustor significantly.

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