Research on Working Characteristics of Pre-combustion Plasma Igniter

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Abstract. In the future, aircraft will definitely move towards a faster and higher goal, and the scramjet is the only way to go. For scramjet engines, reliable and effective ignition is a key to stable combustion in the combustion chamber. Plasma ignition is the research frontier of ignition-assisted combustion technology. This technology consumes low energy, can significantly reduce the minimum energy required for ignition, and increase the rate of chemical reaction. It has obvious advantages for aero engine combustion chambers. In this paper, the working principle of plasma fuel nozzle based on rotating sliding arc discharge is described, and the discharge characteristics of rotating sliding arc are studied on this basis.

1. Introduction

The scramjet is a kind of air-breathing engine, which uses the oxygen in the atmosphere as all or part of the oxidant, and reacts with the fuel it carries to obtain thrust [1]. Compared with the traditional aerospace turbine engine, the structure of the scramjet is relatively simple, but the combustion process inside the combustion chamber and the flow mechanism of the flow field are quite different from the traditional aerospace engine: the entrance of the combustion chamber The air flow is supersonic, which causes the ignition and combustion processes to proceed in supersonic air flow [2]. This new type of combustion organization will inevitably bring a series of problems to the ignition, combustion and flame stabilization of the engine. The key is that the air flow is supersonic and the fuel residence time in the combustion chamber is very short, even reaching the amount of ms. Grade, resulting in the mixing time of the fuel and air and the contact time of the mixture with the ignition source is too short, the fuel cannot be ignited or cannot sustain combustion after ignition.

Plasma is a mixture of freely moving and interacting positive ions and electrons due to the collision of gas molecules to ionize the gas molecules [3]. Foreign scholars use different plasma forms, including microwave discharge, radio frequency plasma, corona and nanosecond discharge, laser plasma, nanosecond pulse discharge, etc., and have carried out a lot of research on the effect of plasma on ignition [4-8]. Domestic research on plasma ignition has been carried out since the 1990s. In recent years, the understanding of plasma ignition has become more systematic, including the effects of different types, different methods, and different conditions on the ignition of plasma. Etc., and achieved a series of results [9-13].

As a periodic reciprocating non-equilibrium plasma generated under normal pressure, the sliding arc has the following two advantages. On the one hand, the electron temperature of non-equilibrium plasma is much higher than the temperature of its neutral and ion, so its average temperature can be adjusted in a wide range. On the other hand, low-temperature plasma has high energy utilization efficiency and good Chemical selectivity.
In response to the important demand of advanced scramjet for plasma ignition and combustion, this paper designs and develops a plasma fuel nozzle with a rotating sliding arc as the discharge form.

2. Working principle of plasma fuel nozzle

The plasma fuel nozzle is mainly composed of eight parts: convergence nozzle, reaction chamber, oil pipeline, bottom sleeve, ventilation base, cyclone, spark plug and atomization nozzle, including two modes of ignition and cracking, and switching between modes depends on the change of oil-gas equivalent ratio. When the fuel gas equivalent ratio is within the ignitable range, the plasma fuel nozzle is in the ignition mode; otherwise, it is in the cracking mode.

When the ignition mode is working, the plasma fuel nozzle is fed with a suitable flow of air to form swirling air through the swirler; the internal spark plug is connected to the sliding arc power supply, and the shell and the sliding arc power supply share the same ground. After the power is energized, a high voltage is generated on the high voltage electrode inside the cavity, and the air between the breakdown and the wall forms a discharge arc; the arc is affected by the swirling air flow and rotates and slides inside the cavity, and finally forms plasma through the convergent nozzle jet; At the same time, the atomized fuel with proper flow and oil pressure is introduced. The swirling air, the gliding arc plasma and the atomized kerosene interact and burn, forming a bright flame that is ejected from the nozzle, and then ignites the mainstream fuel. The ignition measurement system is shown in Figure 1.

When the cracking mode works, the oil-gas equivalent ratio is controlled to be outside the ignitable range, and only cracking reaction occurs inside the nozzle without combustion reaction. At this time, the nozzle outlet jet is a mixture of uncracked kerosene and cracked products. The cracking measurement system is shown in Figure 2.

Figure 1. Ignition measurement system.

Figure 2. Cracking measurement system.
3. Discharge characteristics of rotating sliding arc
The plasma fuel nozzle is a device based on a rotating sliding arc, so the discharge characteristics of the rotating sliding arc are directly related to the working state of the plasma fuel nozzle. The rotating sliding arc is mainly affected by the air flow and the discharge distance, so it is necessary to develop the influence law of the air flow and discharge distance on the discharge characteristics of the rotating sliding arc.

3.1. Discharge characteristics under still air conditions

3.1.1. Discharge characteristics under still air conditions
Under the conditions of still air environment, keep the discharge distance constant at 1mm, change the air flow into the sliding arc, and study the change law of the rotating sliding arc voltage, current and discharge power under different air flow. The range of flow rate changes in the experiment: 0~10L/min, interval 1L/min; 10~50L/min, interval 5L/min; 50~100L/min, interval 10L/min. In the experiment, it was found that the shape of the rotating sliding arc changed significantly at 40L/min, and 90L/min, as shown in Figure 3.

![Figure 3](image)

(a) 40L/min  (b) 90L/min

In summary, when the discharge distance is constant at 1mm, as the air flow increases, the peak-to-peak voltage of the rotating sliding arc discharge gradually increases, while the peak-to-peak current is basically unchanged, and the instantaneous power is basically the same as the voltage waveform. Analyze the reason: the change of the rotating sliding arc discharge channel is a process of constant changes in impedance. With the increase of air flow, the discharge arc is elongated and the arc diameter decreases. The combination of the two makes the discharge impedance gradually increase. When the current peak-to-peak value hardly changes, the voltage peak-to-peak value keeps increasing.

3.1.2. The influence of discharge interval on discharge characteristics
Change the discharge distance to 2–6mm to explore the influence of the discharge distance on the discharge characteristics of the plasma fuel nozzle. It can be seen from the foregoing that when the air flow rate is lower than 10L/min, there is no obvious law for changes in the discharge voltage and current. Therefore, when exploring the influence law of the discharge interval, only the air flow rate after the inflection point is considered. This article selects 10L/min, 40L/min, and 90L/min, as shown in Figure 3. In three air flow states of 90L/min, the change trend of discharge voltage and current cycle, peak-to-peak value and discharge average power at different intervals are examined. The experimental results show that after changing the discharge interval, when the air flow is 10L/min, 40L/min, and 90L/min, the voltage and current period, peak-to-peak value and average discharge power of rotating sliding arc discharge under different discharge interval conditions have no obvious changes. It can be considered that the discharge interval has no effect on the gliding arc discharge.
Block the air circulation and record the peak-to-peak voltage under different discharge spacing conditions. It is found that the peak-to-peak voltage changes significantly. The change rule is shown in Figure 4. The electrode spacing will affect the peak-to-peak value of the initial discharge. As the electrode spacing increases, the peak-to-peak discharge voltage will also increase, which means that the breakdown voltage will also increase.

3.2. Discharge characteristics under supersonic airflow conditions

The blown Laval nozzle is used, and the outlet pressure of the nozzle is the local atmospheric pressure. For the convenience of calculation, the default is the outlet cross-sectional area of the nozzle and the cross-sectional area of the throat. To make the nozzle outlet flow at supersonic speed, it must be ensured that there is no shock wave in the tube. When there is no shock wave in the pipe, the minimum pressure ratio before and after the pipe is 5.6 in the over-expanded working state. Therefore, in order to make the exit of the Laval nozzle a supersonic flow, the pressure ratio before and after the pipe must be higher than 5.6. Taking into account the loss along the pipeline, this experiment selects the initial total pressure of the air source. At this time, the starting pressure ratio is 7.8, and the outlet airflow Mach number $Ma=2.2$, which meets the experimental requirements.

3.2.1. the influence of discharge interval on discharge characteristics

Change the discharge distance to 2~6mm, and explore the influence of the discharge distance on the discharge characteristics of the plasma fuel nozzle under supersonic conditions. From the foregoing, it can be seen that the inflection point flow rate is 25L/min, so the selected air flow state is 25L/min, 40L/min, and 90L/min. After changing the discharge interval, when the air flow rate is 10L/min, 40L/min, and 90L/min, the voltage and current period, peak-to-peak value and average discharge power of rotating sliding arc discharge under different discharge interval conditions have no obvious changes, which can be considered as discharge The spacing has no effect on the gliding arc discharge. Block the air circulation, record the peak-to-peak voltage under different discharge interval conditions, and find that the voltage peak-to-peak value has changed significantly, and the change rule is shown in Figure 5.

![Figure 4. The relationship between the voltage peak-to-peak value and the spacing.](image1)

![Figure 5. Voltage peak-to-peak value under different spacing conditions.](image2)

It can be seen that the peak-to-peak value of the initial breakdown voltage under the condition of supersonic airflow increases with the increase of the discharge interval, indicating that the discharge interval will affect the initial breakdown voltage.

4. Conclusions

In response to the important needs of advanced scramjets for plasma ignition and combustion, predecessors designed and developed plasma fuel nozzles using a rotating sliding arc as the discharge
form. In this paper, the component design and working principle of the plasma fuel nozzle design are described, and the discharge characteristics of the plasma fuel nozzle under two conditions of still air and supersonic air flow are preliminary studied. By changing the air flow into the sliding arc and the discharge interval, the voltage, current and instantaneous power of the rotating sliding arc under different conditions can be obtained; then, the discharge characteristics of the rotating sliding arc under the two conditions are compared. The following conclusions can be obtained:

1) The trend of instantaneous power change and the change of state of rotating gliding arc discharge change synchronously. The voltage peak-to-peak value and average power increase with the increase of air flow, and the voltage and current cycle and current peak-to-peak value are basically unchanged.

2) The discharge distance does not affect the development of the rotating sliding arc, but only affects the breakdown phase at the beginning of the discharge; as the discharge distance increases, the peak-to-peak breakdown voltage between the electrodes also increases significantly.

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