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Experimental study on dielectric barrier discharge plasma-assisted combustion for nozzle

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Abstract. Aiming at the structure of small thrust rocket engine injector, a coaxial shear-type dielectric barrier discharge plasma nozzle was designed, and the effects of methane discharge and air discharge on combustion effect under different excitation and different mixing ratio conditions are studied. The results show that: the flashback occurs when the methane discharge voltage is high, the air discharge can broaden the blow off limit of the air/methane diffusion flame, and has the effect of stabilizing the flame and reducing the lift height.

1. Introduction

In recent years, manned spaceflight has been developed rapidly. In order to improve the safety of human and environment, it is an inevitable trend for spacecraft propulsion system to adopt green non-toxic propellants [1]. Due to the small size of the small thrust rocket engine, the injector is usually a single nozzle structure, coaxial shear nozzle has the advantages of simple structure, good thermal protection performance of the injection panel and so on, which has become one of the solutions commonly used by the injector of the small thrust rocket engine. However, the small thrust rocket engine with chemical fuel is faced with difficulties in ignition, insufficient combustion and instability under low temperature and high vacuum conditions.

The current research shows that plasma has the characteristics of shortening ignition delay time, increasing flame propagation speed and widening the limit of flame extinction [2]. There is a great prospect of using plasma to ignite and assist combustion. The mechanism of plasma-assisted ignition and combustion can be divided into three aspects: thermal effect, chemical effect and aerodynamic effect [3]. Klimov et al. [4] carried out a plasma-assisted combustion experiment of propane fuel under supersonic conditions, and found that plasma can significantly expand the fuel's rich limit and lean limit and reduce the ultimate combustion temperature. Singleton et al [5] used a transient plasma igniter (TPI) to test the ignition of ethylene/air. By improving the electrode life and using low-energy multi-point ignition, it is verified that TPI has the potential to improve combustion efficiency and can be widely used in rocket engines technology. Kim et al [6] used the method of dielectric barrier discharge with needle-needle electrode to verify that the non-equilibrium plasma can stabilize the flame by changing the gas flow velocity. It is believed that the activation of plasma plays a major role. Pilla G [7] et al. studied the combustion assistance effect of nanosecond pulsed plasma on propane air turbulence premix flame under atmospheric pressure, and found that nanosecond pulsed plasma significantly improved the flame stability and combustion efficiency, and broadened the flammability limit. Yuzhu Ding [8] measured the methane DBD discharge and combustion flame by spectrometer, and combined with fluent simulation, it is concluded that the improvement of methane combustion characteristics by DBD discharge is caused by the active groups such as CH3 and H generated by methane discharge dissociation. At present, the research on coaxial-shear plasma nozzle assisted methane combustion is relatively scarce, and further research is needed.

In this paper, a coaxial shear-type dielectric barrier discharge plasma nozzle is designed for the structure of small thrust rocket engine injector, and the experimental study of plasma-assisted methane combustion is carried out. The effects of methane discharge and air discharge on flame morphology and combustion-supporting effect under different excitation and different mixing ratio conditions are studied, and the mechanism of plasma-assisted methane combustion is analyzed.

2. Experimental Facilities

The experimental system consists of excitation power supply, nozzle, piping system, measurement equipment and camera, etc. The schematic of the experimental system is shown in Figure 1.

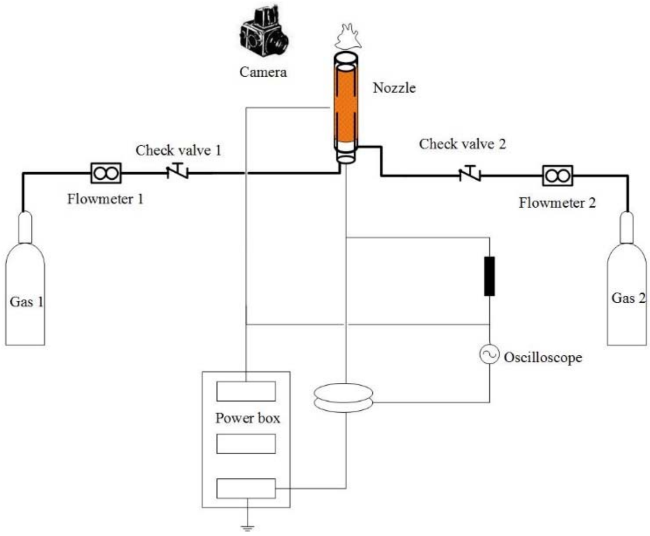
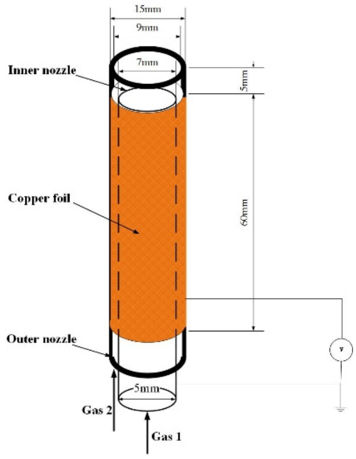


Figure 1. The schematic of the experimental system.

The excitation power supply adopts the HFHV30-1 high-frequency high-voltage power supply developed by the Institute of Electrical Engineering of the Chinese Academy of Sciences. The output voltage is 0 ~ 30kV, and the waveform is sine wave, which has two working modes: continuous and pulse. In continuous mode, the output frequency is 1~50kHz. In pulse mode, the pulse frequency and duty cycle are adjustable. The minimum frequency and minimum duty cycle are 10Hz and 10% respectively.

The voltage is measured with an Agilent N2771B high voltage probe, the current is measured with a Pearson current coil 6595, and the voltage and current measurements are displayed and recorded using a Tektronix DPO 2024 oscilloscope.

The structure diagram and physical diagram of the nozzle are shown in Figure 2. The nozzle adopts a coaxial structure, and the length of the indented section of the nozzle is 6 mm, wherein the inner nozzle has an inner diameter of 5 mm and an outer diameter of 7 mm, and is made of stainless steel and serves as a ground electrode during discharge. The outer nozzle has an inner diameter of 9 mm and an outer diameter of 15 mm. The material is an alumina ceramic with a dielectric constant of 9.5 and serves as a dielectric layer for discharge. The high-voltage electrode is made of copper foil and adhered to the surface of the outer nozzle, horizontally to the inner nozzle, and has a length of 60 mm. After high voltage excitation, the nozzle can form a discharge region in the annular slit region of 60mm, acting on the flowing gas to produce plasma. The high-precision flowmeter is used to control the gas flow rate, and the accuracy of the flowmeter is 2.5‰.



(a) The schematic of the nozzle.


(b) The physical diagram of the nozzle.

Figure 2. The schematic and physical diagram of the nozzle.

3. Plasma-Assisted Combustion Experiment

In the process of combustion, molecules, atoms and free radicals in the flame will gain energy to jump from the ground state to the excited state. The excited state particles themselves are unstable, and will spontaneously jump from the high energy level to the low energy level. At the same time, they radiate light with corresponding energy, which is called spontaneous emission. Due to the different wavelengths of spontaneous emission of different particles, different bands of filtering devices can be used according to requirements to achieve imaging of specific components. Spontaneous emission does not require high energy lasers and complex optical devices and does not require additional energy supply. Spontaneous emission signals need only simple equipment, simple and efficient, and are widely used in the diagnosis of combustion field.

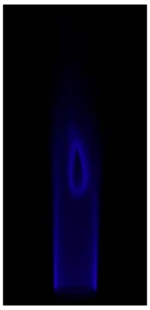
In the combustion flame of methane and air, CH (A-X) with a wavelength of 430nm is one of the main sources of luminescence, so the spontaneous emission of CH (A-X) can be used as an important basis for judging the combustion situation. The filter plate is used to select the emission wave passing through a specific wavelength, and the transmission rate of CH (A-X) emission wave at 430nm is about 86%. The filter plate is installed into the camera lens to capture the spontaneous emission of CH (A-X) under different conditions.

Methane and air are introduced from different passages of the nozzle at a specific flow rate, and mixing occurs in the nozzle retraction section. The mixture gas is ignited by a pistol igniter. After the flame combustion is stabilized, the high frequency alternating current power source is used to apply excitation to the nozzle, and the flame change under different voltages is observed and recorded by the photographing device. In order to avoid the contingency of the experiment, multiple pictures were taken for each working condition.

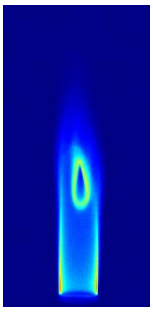
Due to the different types of active particles produced by methane and air discharge, there may be different effects in performing plasma-assisted combustion. Therefore, the research conditions are divided into two categories: methane discharge and air discharge, and different flow rates and mixing ratios are adjusted to study the effects of different excitation voltages on the flame morphology.

3.1. Methane Discharge Plasma-Assisted Combustion Effect

Air was introduced from the metal nozzle, methane gas was introduced from the outer nozzle of the annular slit, and the methane flow rate was maintained at 0.6 L/min. The mixing ratio was changed by adjusting the air flow rate to study the effect of methane discharge on the flame morphology under different mixing ratios. The air flow rate was adjusted to 2.86 L/min, and the mixing ratio φ=2 at this time was rich combustion. After the gas is ignited, the voltage is gradually increased to discharge the methane, and the flame shape at different voltages is recorded. In order to remove the background noise, a certain filtering algorithm is used to write the Matlab program to process the spontaneous emission image of flame obtained by the shooting. The spontaneous emission image of the flame and the processing result without excitation are shown in Figure 3.



(a)Before process



(b) After process

Figure 3. The spontaneous emission image of the flame (0kV).

The spontaneous emission image of the flame under different excitation voltages during the experiment is shown in Figure 4. It can be seen from the figure that in the undischarged case, since the flame is a non-premixed flame, the central part is mainly air, and the methane concentration is lower than the ignition limit, so there is a hollow area in the middle of the flame, and the whole is in a ring shape. The spontaneous emission intensity at the exit of the annular slit is large, and the light intensity decreases along the exit direction of the annular slit. As the discharge voltage increases, the flame shape changes significantly: when the voltage is 6kV, the flame gathers toward the center, the shape becomes slender, the central annular region increases, and the annular position decreases, which is due to the breakdown of methane. Under the action of discharge aerodynamic effect, the jet turbulence increases, which enhances the mixing effect of methane and air. With the increase of voltage, the ring region increases, the ring position decreases, the flame length increases slightly, and the spontaneous emission intensity decreases at the bottom. When the voltage is increased to 12kV, the flame begins to develop toward the nozzle retracting section, flashback occurs, and the flame length begins to shorten. When the voltage is 14kV, the central ring region disappears and the flame length is significantly shortened.

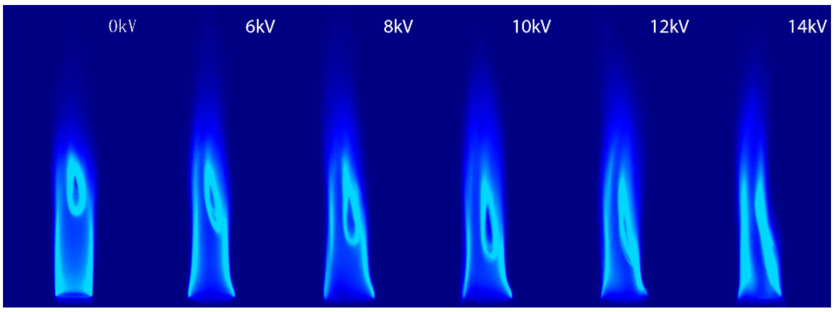


Figure 4. Flame under different excitation voltages of methane discharge (φ=2).

When the air flow rate is increased to 5.7 L/min, the mixing ratio φ=1, which is the theoretical mixing ratio. The change of flame morphology is shown in Figure 5. The increase of air flow rate provides more oxidants for methane combustion, and the velocity difference between air flow and methane flow becomes larger, the shear effect of air flow is more obvious, and the mixing effect is enhanced. Methane is more fully burned than under the condition of rich combustion. The variation of flame morphology with the increase of voltage is similar to that under the condition of rich combustion.

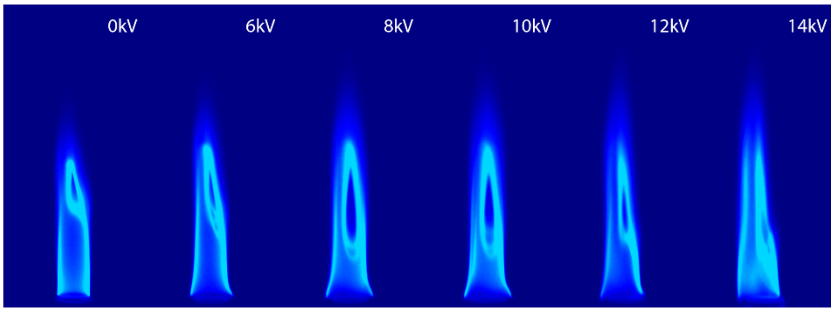


Figure 5. Flame under different excitation voltages of methane discharge (φ=1).

When the air flow rate continues to increase to 9.5 L/min, the mixing ratio φ = 0.6, which is a lean combustion state. The change of flame shape in the experimental process is shown in Figure 6. When not discharged, the flame length becomes shorter than before, and has good symmetry. The hollow area of the flame gradually becomes smaller as the flame develops, forming a circular hole at the tip of the flame. When the voltage is increased to 6kV, the small hole disappears, the flame is completely closed, and the whole is tapered. As the voltage increases, the flame length increases slowly.

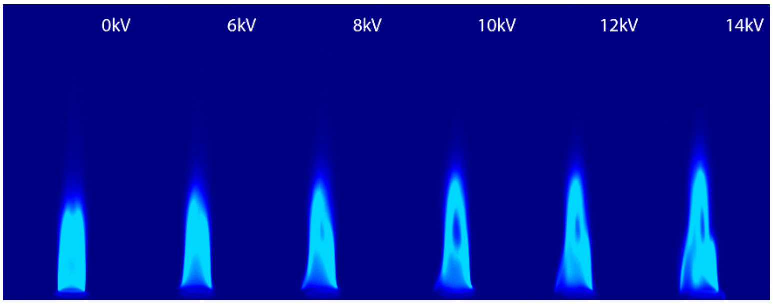


Figure 6. Flame under different excitation voltages of methane discharge (φ=0.6).

3.2. Air Discharge Plasma-Assisted Combustion Effect

In order to study the effect of air discharge on the flame shape, the outer nozzle of the annular slit is introduced into the air, and the inner nozzle is introduced with methane gas. The gas flow rate is adjusted by Flowmeter and the air flow rate is kept at 3 L/min. The methane flow rate is changed and the effect of air discharge on the flame is observed under different mixing ratios. The flow rate of methane was adjusted to 0.63 L/min through a flow meter. At this time, the mixing ratio φ=2, the flame morphology at different voltages was recorded, and the spontaneous emission image of the flame was processed by the method described in the previous section. The processing results are shown in Figure 7. When the voltage is not applied, the flame is separated from the nozzle because of the high velocity of the gas, and the lifted flame is formed and sloshing continuously. As the excitation voltage increases, the flame begins to stabilize and gradually approaches the nozzle, and the lift height decreases. The flame spontaneous emission intensity is concentrated at the bottom of the flame, and there is a hollow region at the bottom of the flame; as the excitation voltage increases, the hollow area is reduced, indicating that the discharge enhances the methane air blending and the combustion is more complete.

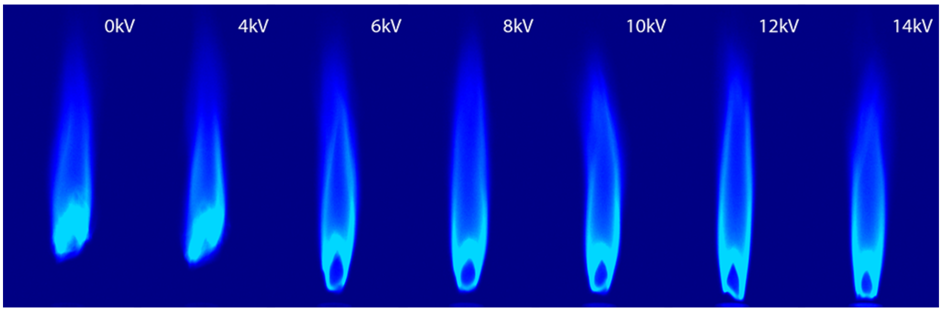


Figure 7. Flame under different excitation voltages of air discharge (φ=2).

Adjusting the flow rate of methane to the theoretical mixing ratio (φ=1) and using the pistol igniter failed to ignite many times, which shows that the current working condition is beyond the blowoff limit. When the power supply is turned on, the air discharge occurs, the voltage increases step by step, and the igniter is constantly tried to ignite. When the voltage increases to 11kv, the ignition is realized successfully. As shown in Figure 8: the flame is the lifted flame, and the flame length is significantly shorter than the rich state (φ=2). As the voltage increases, the flame lift height decreases. The voltage is gradually reduced, and the flame is again blown out.

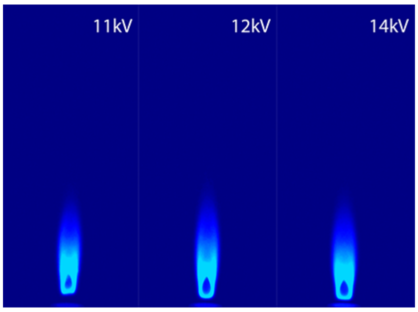


Figure 8. Flame under different excitation voltages of air discharge (φ=1).

When the methane flow rate is reduced to the mixing ratio φ=0.5, it is obviously beyond the blowoff limit. When the voltage increases to 12kv, the ignition is realized successfully. The flame is shown in Figure 9: the flame is shorter and suspended above the nozzle. When the voltage is increased to 14 kv, the flame lift height decreases and the length increases slightly. Lower the voltage and the flame will blow out as well.

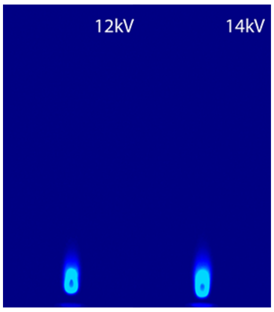


Figure 9. Flame under different excitation voltages of air discharge (φ=0.5).

The actual height is obtained by processing the flame image taken, and the variation of the flame lift height with different mixing ratio with voltage is shown in Figure 10. It can be seen from the diagram that the flame lift height decreases with the increase of the voltage, and increases with the decrease of the mixing ratio when the air flow rate is constant.

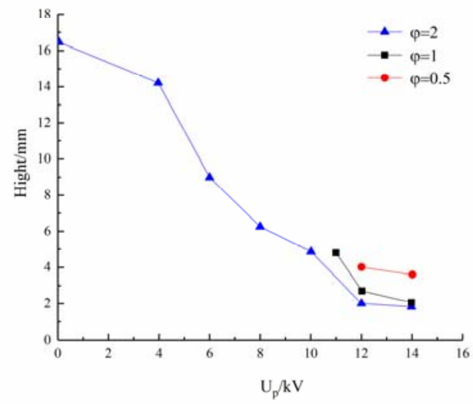


Figure 10. Flame lift height under different excitation voltages and different mixing ratios

4. Conclusion

In this paper, a coaxial shearing dielectric barrier discharge nozzle is designed for the injector configuration of small thrust rocket engine. The experimental platform is built to carry out the relevant research. The main conclusions are as follows:

(1)When the methane discharge voltage is high, the flashback occurs. For the rocket engine nozzle, it is generally not desirable for the retraction section temperature to be too high. Therefore, the appropriate voltage should be selected to achieve better results.

(2) The air discharge can broaden the blowing limit of the air/methane diffusion flame, and has the effect of stabilizing the flame and reducing the lift height. As the discharge voltage increases, the flame lift height gradually decreases.

Acknowledgments

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