

Article

Experimental Investigation on Flow Characteristics and Ignition Performance of Plasma-Actuated Flame Holder

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Abstract: Improving the performance of flame holders has been a key focus of research on ramjet combustors. The plasma actuator has the potential to improve the ignition performance by manipulating the flow field of the flame holder. In this study, a plasma-actuated flame holder was designed. The aim of this study is to improve the performance of ramjet combustor by applying plasma discharge to the flame holder. The aerodynamic effects and ignition performance of the flame holder were investigated. The results demonstrated that the induced jet direction of the surface arc discharge was perpendicular to the actuator. The induced jet dissipated faster at lower pressures. The aerodynamic actuation intensity and jet area increased with the number of channels of surface arc discharges. Increasing discharge frequencies can increase the discharge times and jet height. The aerodynamic effects under a microsecond pulse duration were better than those under a nanosecond pulse duration. Actuators installed on the inside surface showed better performance than those installed outside. Under different total flow temperature conditions, the plasma-actuated flame holder significantly extended the ignition pressure limit and increased the combustion efficiency by 9.12% and 4.3% on average, respectively.



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Keywords: plasma-actuated flame holder; low velocity area; fuel-air mixture residence time; ignition process; ignition pressure limit; combustion efficiency

1. Introduction

Reliable ignition and stable combustion of ramjet combustors are difficult to achieve due to the high gas velocities. The flame holder is an important component used to stabilize the flame during ramjet combustion. The flame stability largely depends on the flow field downstream of the flame holder. Therefore, the ignition reliability of the combustion chamber is expected to improve with an improved wake flow field of the flame holder.

The research on flame holding goes back to 40–60 s [1–6]. And a number of studies have been conducted to investigate and improve the flame stability of flame holders. Jin et al. [7] conducted a numerical simulation on the flow field of the flame holder, and the results showed that the width of the groove had the greatest influence on the characteristics of the recirculation zone. The recirculation zone increased with the width of the groove, but so did the total pressure loss. Sirka et al. [8] found that the flow form of the flame holder was determined by the heat conduction of the flow wake. Prior et al. [9] found that the vorticity at the end of the V-shaped flame holder greatly influenced mixing, and that the characteristics of the shear layer and recirculation zone were important factors affecting flame stability. Hosokawa [10] studied the structure of the recirculation zone and found that the velocity vector at the end of the flame holder determined the scope and shape of the recirculation zone. Moreover, he added a rectangular section to the V-slot to analyze the recirculating region and flow oscillation of the flow field. It was found that the recirculation zone was reduced and the oscillation frequency increased after the rectangle section was added to the V slot. Li et al. [11] studied the flow characteristics of a V-shaped flame holder at low pressure and found that the size of the recirculation zone decreased with a

decrease in pressure. Du et al. [12] found that the resistance characteristics of streamlined flame holders were better than those of non-streamlined flame holders, but the size of the recirculation region of the former was smaller than that of the latter. Yue et al. [13,14] proposed the a viewpoint of a flame stabilization mechanism, and analyzed the importance of the role of alternate generation and shedding of vortices during the process of flame stabilization. Wang et al. [15] measured the flow field in a V-slot with a hot-wire instrument and found that the flow rate and range of the recirculation zone reduced with a decrease in pressure.

In previous studies, the stability of the flame holder was improved by changing its structure. The application of plasma in improving the flow field structure, broadening the ignition boundary [16,17], and improving the ignition reliability and combustion efficiency [18–20] has attracted the attention of a number of researchers. Many kinds of plasmas are applied to dielectric barrier discharges [21], plasma jets [22], gliding arcs [23], AC plasmas [24], arc discharge [25] torches [26], sparks [27] OH laser-induced [28] etc. Arc discharges have been studied extensively in the field of flow control. Lan et al. [29] studied the jet characteristics of arc discharges, and the results showed that an arc discharge characteristically has a large amount of energy and strong penetration ability. Chintala et al. [30] found that the pulsed arc discharge can significantly improve its stability under the actuation of short pulses. With regards to flow control, the discharge energy and intensity are important factors affecting flow control effects. The disturbance effect of the flow field increases with an increase in the energy added to the flow field [31]. The temperature of a surface arc can be as high as 3000 K, which can reduce the shock wave angle by 8.6% [32]. According to the design method of plasma, synthetic jet actuators with multiple discharge channels, as proposed by Zhang et al. [33], a multi-channel arc discharge actuator is realized. In He's study, the flow control effect increases with the increase of the actuation frequency. When the actuation frequency reaches 1 kHz or 2 kHz, the flow separation is completely controlled [34]. The results of Zhang's work show that the intensity of two separation shock waves decreases under the control of high-energy streamwise pulsed arc discharge array, which verifies the feasibility of arc discharge array to control the double compression ramp shock wave/boundary layer interaction [35].

Although it has been found that plasma flow control is an effective method, the research regarding plasma-actuated flame holders is still rarely reported. The effect of the plasma actuator on the flow field structure and the ignition boundary of flame holders is still unknown. In this study, a plasma-actuated flame holder was designed to explore the aerodynamic actuation and ignition characteristics.

2. Experimental Setup

2.1. Model of Flame Holder

A flame holder model with a surface measuring 102 mm by 29 mm was used in this study. The flame holder was made of stainless steel. The groove of the flame holder was 45 mm wide. The extension lines on the upper and lower surfaces formed an angle of 40 degrees, also referred to as a V-shaped flame holder. The surface arc discharge actuator was installed on the upper surface of the flame holder as shown in Figure 1. The electrodes were symmetrically distributed at the center of the upper surface. The electrode spacing, b , was 3 mm, and the distance between the actuator and the trailing edge of the flame holder, d , was 2 mm. A spark igniter was installed on the side of the flame holder.

2.2. Schlieren Imaging System and PIV Measurement System

A schematic of the schlieren imaging system is shown in Figure 2. DBD is short for Dielectric Barrier Discharge. The DG535 is a type of signal generator designed to trigger a high-speed camera at the same time of discharge for synchronous recording purposes. It consists of a high-speed camera (Phantom-v5012) for taking images, a xenon lamp that continuously emits intense white light, two concave mirrors and two blades. The high speed camera (Phantom-v5012) captures static flow field features with an exposure

time of $1.2\ \mu\text{s}$ at a frame rate of 100,000 fps. The image resolution of the high speed camera was 1024×208 pixels, but to obtain a clearer flow field, the visual image was cut to 502×202 pixels. There are two blades in the schlieren imaging system, one was used to block some of the light, and the other was placed in front of the high-speed camera to improve the sensitivity of the visualizations.

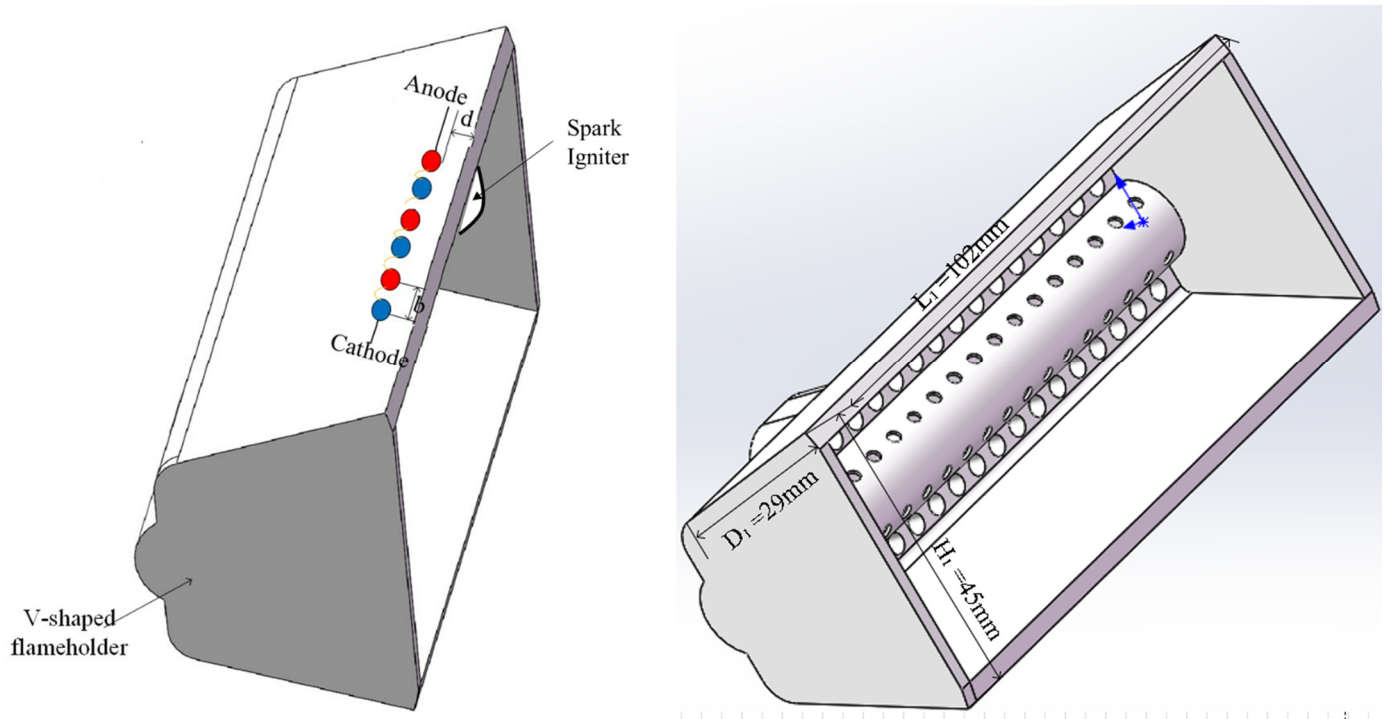


Figure 1. Schematic of the flame holder model.

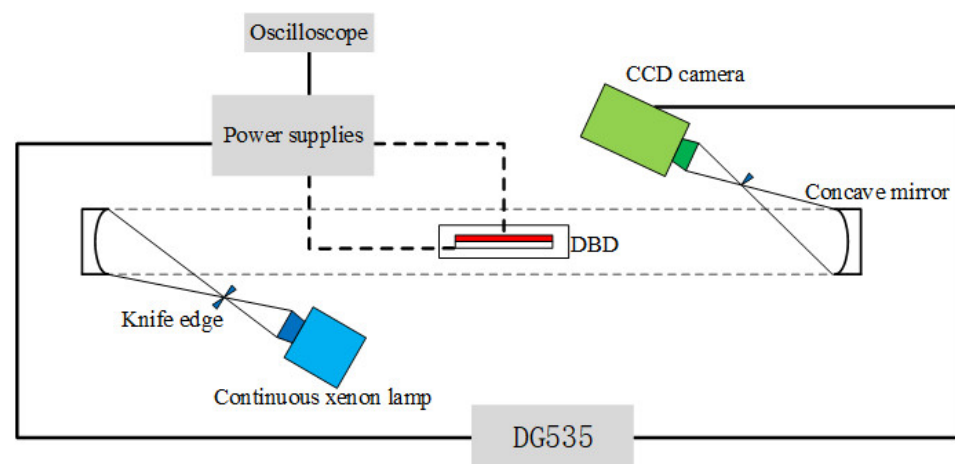


Figure 2. Schematic of the Schlieren imaging system.

Particle image velocimetry (PIV) allows us to study the influence of arc discharges on aerodynamic actuators, as shown in Figure 3. The PIV measurement system adopted a dual-pulse Nd: YAG laser. The laser energy was 540 mJ with a wavelength of 532 nm. The CCD camera was used to capture the tracer particle picture, at a pixel resolution of 1600×1200 . The maximum acquisition frequency of the CCD camera was 10 Hz. The tracer particle used in the flow field was olive oil, which was produced by pressure atomization. Davis 8.3 software was used to process and calculate the data captured by the PIV system.

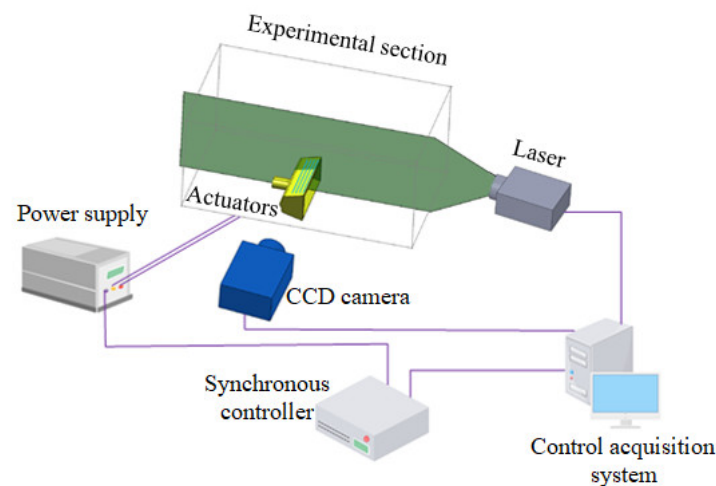


Figure 3. Schematic of the PIV measurement system.

2.3. Directly Connected Ramjet Combustor Test System

The directly connected ramjet combustor test system simulated the temperature, pressure, speed and other extreme conditions at the inlet of the ramjet combustion chamber. The schematic diagram of the directly connected ramjet test system is shown in Figure 4. The directly connected ramjet test system consisted of an electric heater, rectifying section, combustion chamber, and ejection system, which could simulate a maximum inflow rate of 1.5 kg/s. Air is supplied at the front end, heated by the electric heater, and reaches the set speed after passing through the internal throat. A steady flow is achieved in the rectifying section before entering the combustion chamber. The outlet of the electric heater was directly connected to the entrance of the combustion chamber, and the outlet of the combustion chamber was connected to the throat and ejection system in turn. The electric heater raised the inlet air temperature up to 500 K. The inlet Mach number varied by adjusting the downstream throat characteristics. In this study, we kept the Mach number at 0.2. When the Ma number is 0.2, the air flow is 0.78 kg/s. The primary function of the ejection system was to inject the suction flow so that the combustor experienced a negative pressure state. Two rectangular quartz glass windows were installed on the side of the combustion chamber. The primary function of which was to observe and record the ignition process synchronously. The ignition process was recorded with a high speed camera, which was set at a frame rate of 20,000 fps at a resolution of 1280×800 and an exposure time of 49 μ s. The fuel used in this paper is aviation kerosene. The working fluid is dry air provided by an air compressor.

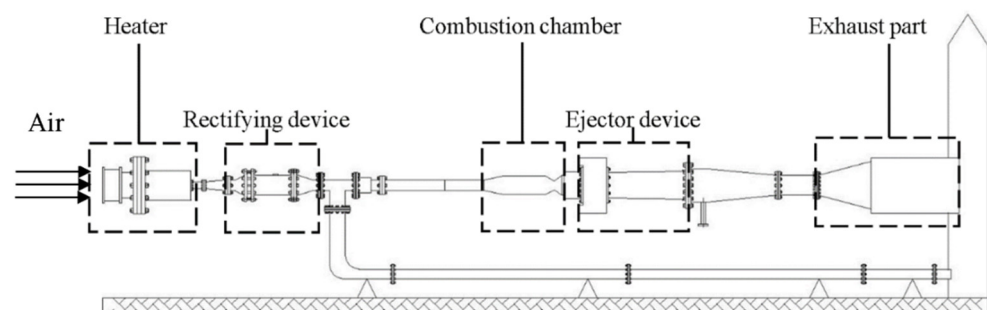


Figure 4. Schematic of the direct connected ramjet test system.

3. Results and Discussion

3.1. Plasma Aerodynamics Actuator Characteristics

The influence of the ambient pressure and discharge channel on plasma aerodynamic actuation is experimental, and further discussed in this section.

The schlieren imaging of the arc discharge at different pressures (30 kPa–101 kPa) is shown in Figure 5. As observed, the surface arc discharge generates a semicircular shock wave and induced jet flow at the same time. The induced jet flow is in the vertical upward direction. The intensity of the shock wave and jet flow at 70 kPa is higher than that at atmospheric pressure due to the better impedance matching of the power supply. Then, from $P = 70$ kPa to $P = 30$ kPa, the intensity of the shock wave reduces as the pressure decreases. The jet flow dissipates faster at lower pressures. According to Paschen's law, the breakdown voltage reduces with a decrease in pressure. The arc discharge has negative impedance characteristics, resulting in the current decreasing in the circuit, leading to decreased energy deposition. The deposited energy from an arc discharge heats the gas and causes it to expand, resulting in a shock wave being generated. The impact of the shock wave then generates the convective jet flow.

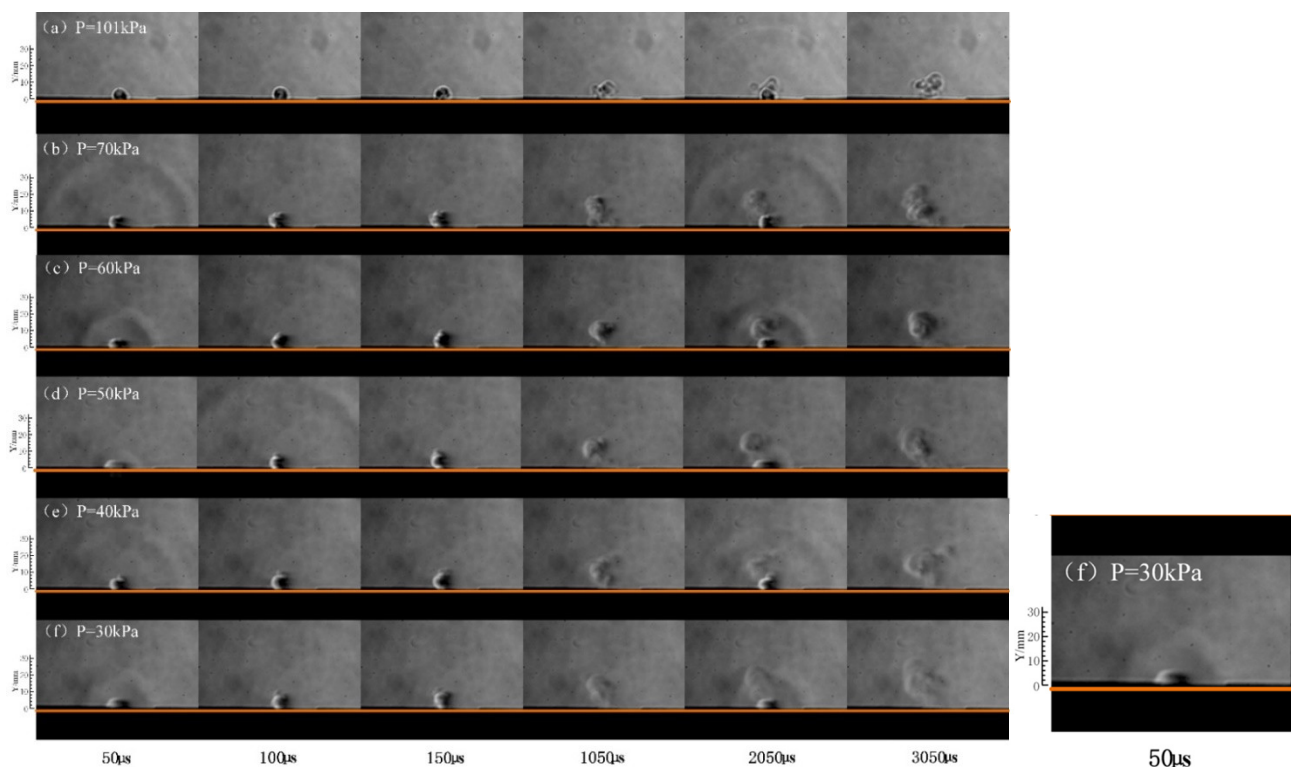


Figure 5. Schlieren imaging at different pressure.

Figure 6 shows the schlieren imaging arc discharge under different channel numbers at $P = 30$ kPa and $P = 70$ kPa. Through comparative analysis, we observed that the jet intensity and affected area, induced by the arc discharge, increased along with the number of discharge channels. There was a positive correlation between the jet height and discharge time. The reasons may be that the increase in the number of discharge channels led to an increase in the arc discharge area. Furthermore, an increase in the number of discharge channels ensured that the input voltage was greater than the breakdown voltage; thus, the input voltage would increase, as would the jet intensity and affected area. In addition to the continuous discharge of surface arcs, subsequent discharges were carried out before the jet dissipated completely, and the jet generated by the last discharge was pushed further outward. Therefore, the intensity of the surface arc discharge can be controlled by changing the discharge frequency. By comparing Figure 6a,b, it can be observed that, consistent with the plasma aerodynamics actuation caused by the above single-channel surface arc, the jet intensity and shock wave generated by the multi-channel surface arc increased with an increase in air pressure.

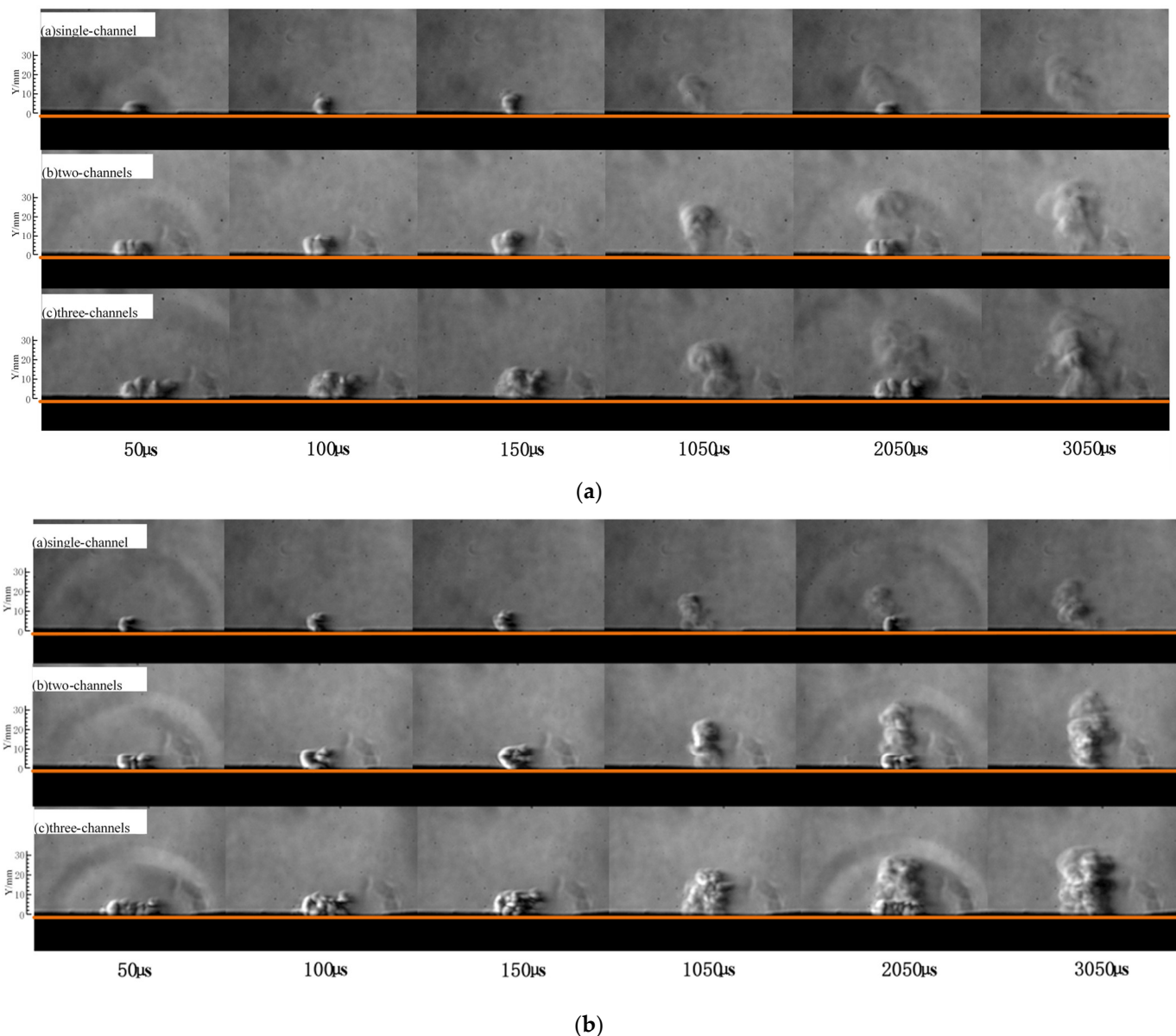


Figure 6. Schlieren imaging at different channel numbers (a) $P = 30$ kPa, (b) $P = 70$ kPa.

3.2. Flow Field Characteristics of Plasma-Actuated Flame Holder

To further verify the feasibility of using a plasma arc discharge actuator to improve the performance of the flame holder, the PIV system was used to explore the flow field characteristics.

Under the conditions of air pressure of 40 kPa, 50 kPa, 60 kPa and 70 kPa, the PIV test was carried out on the wake flow field of the vaporizer flame stabilizer without plasma excitation, as shown in Figure 7. It can be seen from the figure that starting from the wake of the flame stabilizer, the high-speed fluid outside the flame stabilizer and the low-speed fluid inside form a clear boundary area, which is the shear layer. When the ambient air pressure is higher than 50 kPa, the structure of the recirculation zone is asymmetrical, the streamline of the lower recirculation zone is not closed, there is a certain range of low-velocity zone ($V < 1$ m/s) but no complete vortex core is formed, which may be due to the flame Caused by the change of the Karman vortex street after the stabilizer. The length of the recirculation zone increases with the increase of the ambient air pressure, and the vortex center gradually moves downstream, indicating that with the increase of the air pressure, the flame range that the flame stabilizer can stabilize is wider. The recirculation zone length is defined as the distance from the end of the flame holder to the furthest boundary of the

recirculation zone. When the ambient air pressure is lower than 50 kPa, the structure of the recirculation zone presents a symmetrical structure, with a closed recirculation zone and a certain range of low-speed zones at the upper and lower sides.

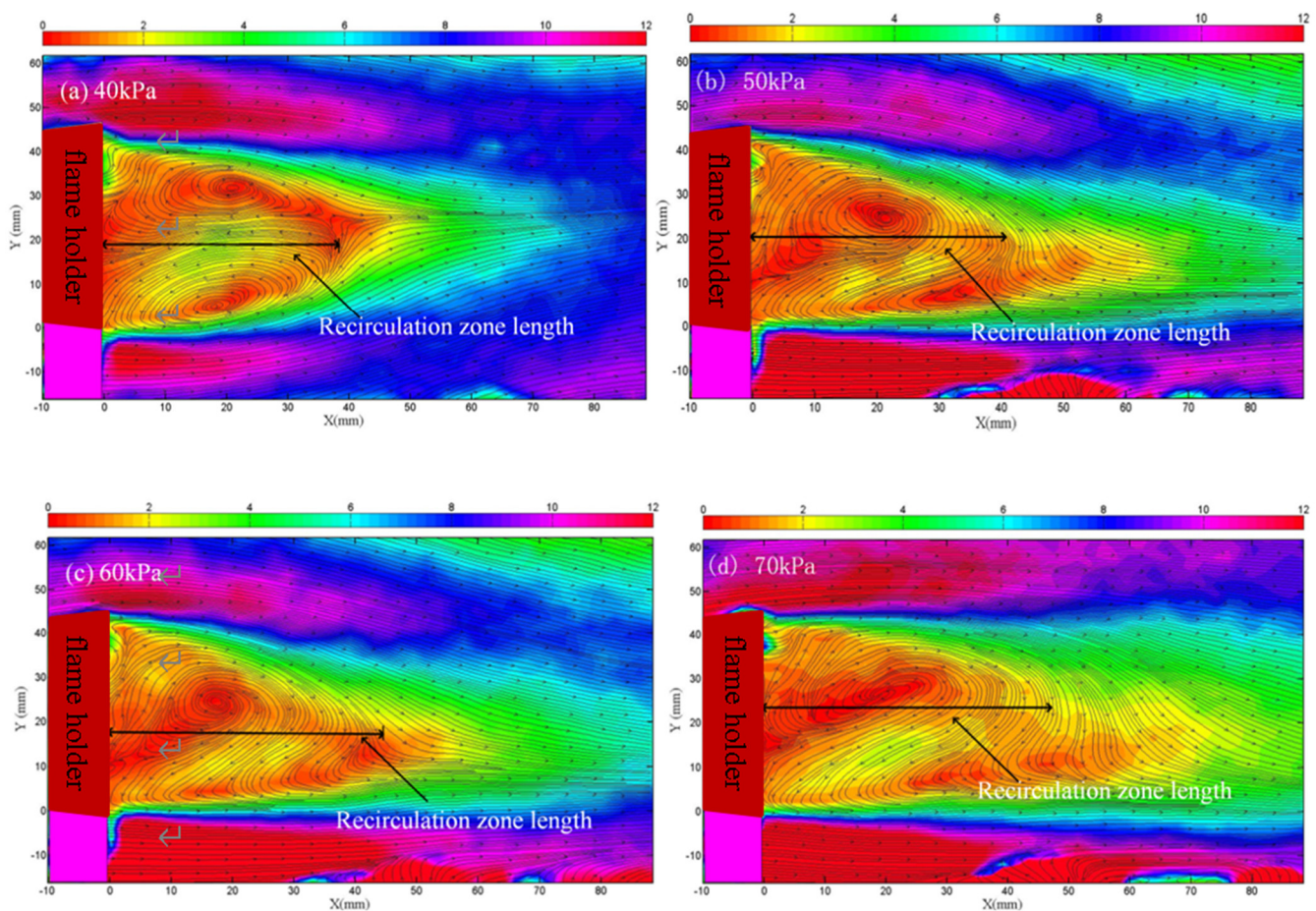


Figure 7. Flow field structure diagram of evaporating tube flame stabilizer under different pressures.

The low-velocity region of the recirculation zone is a key parameter of flame holder. In this section, the velocity contour of the flow field around the flame holder was obtained using the PIV measurement system. The low velocity area (LVA) was defined as the area where V was less than 1 m/s. The ability of the flame holder to establish a stable flame depends on the fuel-air mixture residence time (FMRT) in the recirculation zone [36]:

$$\tau_{res} = \frac{(L/2)}{(V_2/2)} = \frac{L}{V_2} \quad (1)$$

where, L is the length of the recirculation zone of the flame holder wake; and V_2 is the velocity at the edge of the recirculation zone. According to the Mikhelson criterion, $M_i = \frac{\tau_{res}}{\tau_b}$, if $\tau_{res} < \tau_b$, if the residence time of the fuel-air mixture is less than the combustion time, the flame is likely to be blown away from the circulation zone and extinguished. Theoretically, a larger FMRT can improve flame stability.

(1) Effect of discharge frequency on aerodynamic actuation

A comparison of the LVA and FMRT at different frequencies are shown in Figure 8 at various ambient pressures. The analysis shows that when the ambient pressure is higher than 60 kPa, the LVA increases with an increase in the discharge frequency. In the selected experimental frequency range, where the optimum frequency was found to be 1000 Hz, the LVA could be increased up to 38.7%. At the same discharge frequency with a decrease in environmental pressure, the LVA could not be increased. However, when the discharge

frequency was 100 Hz, the LVA could be increased from 1.44 cm² to 2.699 cm², which is 87.4% higher than that when the frequency is 0 Hz, when the air pressure was 60 kPa. This shows that the inherent characteristic frequency of the flow field changes, and that the instability and difficulty of manipulating the flow field increase with a decrease in pressure. The applied plasma actuator maximizes the manipulation when the discharge frequency is coupled with the characteristic frequency of the flow field. At the same time, it also shows that the nanosecond pulsed plasma arc surface actuator greatly improves the flow field of the flame holder's wake. The main reason being that the higher jet intensity generated by the multichannel surface arc, which deposits energy into the flow field.

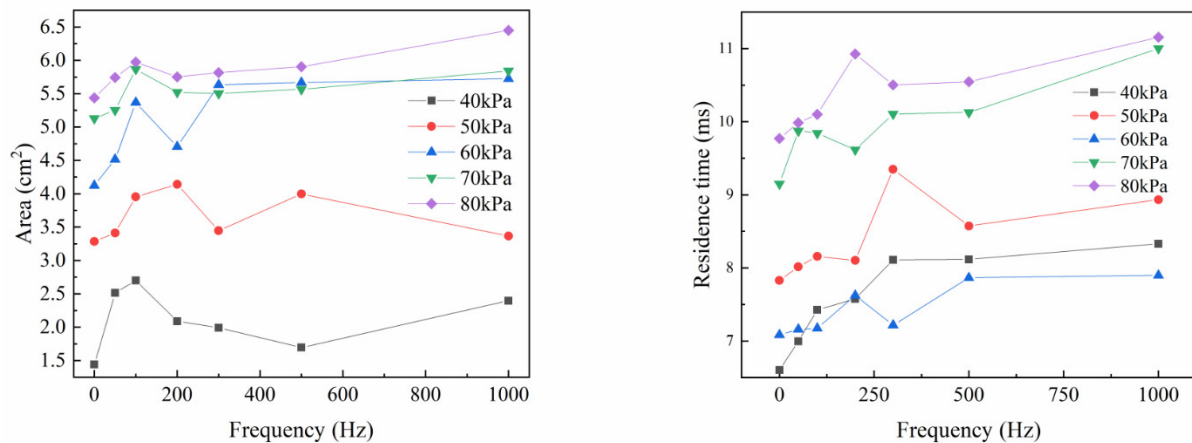


Figure 8. Comparison of the LVA and FMRT to the frequency.

Figure 8 shows the FMRT curves for different discharge frequencies. It can be seen from the figure that the FMRT is positively correlated with the frequency. Within the selected frequency range, the optimal frequency is 1000 Hz, and the FMRT can be increased by 26.8%, 14.1%, 11.5%, 20.2% and 14.2%, for pressures of 40, 50, 60, 70 and 80 kPa, respectively. Furthermore, under the optimal frequency, the flow field manipulation effect becomes more obvious with a decrease in ambient air pressure. Therefore, the optimal frequency of the plasma surface arc discharge is 1000 Hz.

(2) Effect of pulse width on aerodynamics actuation

Figure 9 shows the LVA and FMRT as a function of discharge pulse width. The flow field manipulation effect is better at pulse widths of microseconds than that of nanoseconds. When the pulse width is longer than the optimal duration, the increase of the pulse width has no obvious effect on the flow field manipulation and reaches a saturation state. Table 1 summarizes the LVA and FMRT extension with optimal pulse width from 40~80 kPa. It shows that the optimal pulse width always achieves at the microsecond level, and there is a proportional relationship between the optimal pulse width and ambient pressure.

Table 1. LVA and FMRT extension with optimal pulse width.

Pressure	LVA Extension	FMRT Extension	Optimal Pulse Width
40 kPa	134%	23%	5000 ns
50 kPa	52.1%	52.1%	5000 ns
60 kPa	41.3%	14.5%	10,000 ns
70 kPa	28%	9.6%	5000 ns
80 kPa	30.7%	8%	1000 ns

The following conclusions can be drawn from the above observations. On one hand, at low pressures, the direction of jet produced by the arc is close to the vertical upward, and the jet intensity decreases with a decrease in pressure, resulting in a limited disturbance to the flame holder flow field. On the other hand, the jet generated by the surface arc actuator

compresses the mainstream upward, which reduces the flow area and increases the velocity of the mainstream at the flame holder wake. Consequently, the length of the recirculation zone will increase and the LVA and FMRT will increase accordingly.

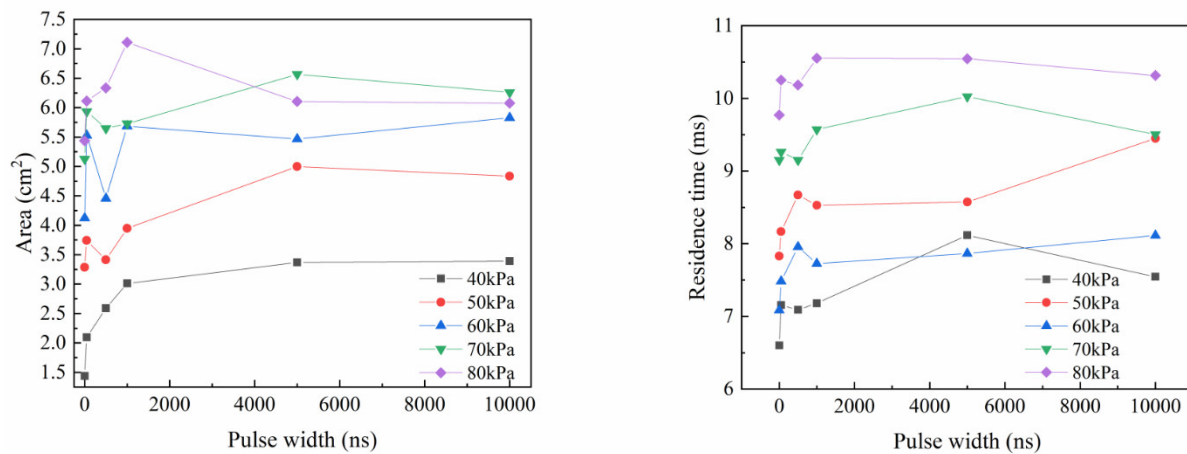


Figure 9. Comparison of the LVA and FMRT to the pulse width.

(3) Effect of rising edge on aerodynamic actuation

Within the selected experimental pressure range, the LVA is positively correlated with a rising edge of applied voltage, but the growth rate of the LVA decreases with an increase of the rising edge as shown in Figure 10. When the pressure was 40 kPa, 500 ns was the optimal value for the rising edge, and the LVA could be increased by 88.5%. At other pressures, the LVA could be increased by 33.6% on average. Table 2 summarizes the extension with optimal rising edge from 40~80 kPa.

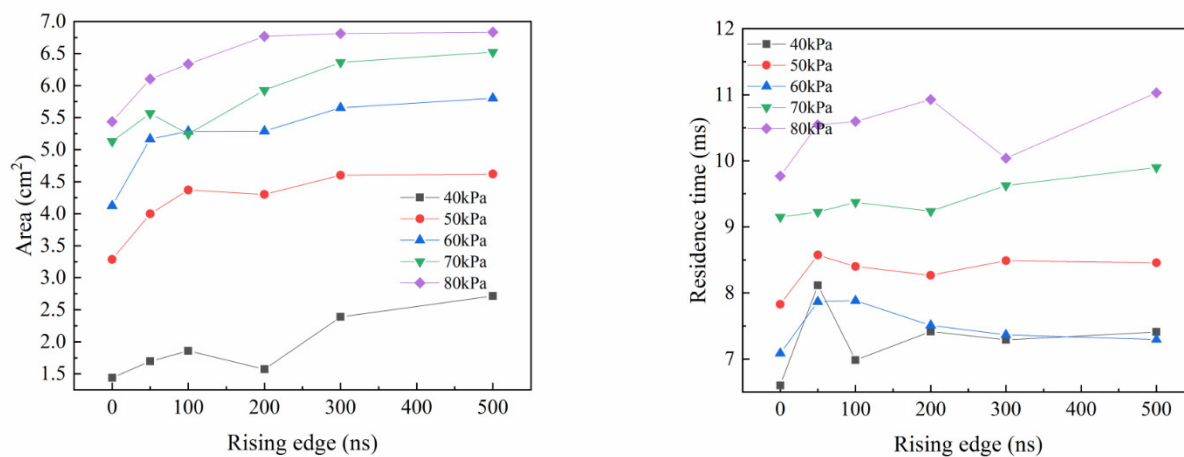


Figure 10. Comparison of the LVA and FMRT to the rising edge.

Table 2. LVA and FMRT extension with rising edge.

Pressure	Lva Extension	Optimal Rising Edge
40 kPa	18.7%	50 ns
50 kPa	9.5%	50 ns
60 kPa	11.3%	100 ns
70 kPa	8.2%	500 ns
80 kPa	12.9%	500 ns

The reasons are as follows: with the decrease in ambient air pressure, the flame holder wake flow field becomes more complex and the characteristics of the flow field change.

Therefore, greater discharge intensity is needed to effectively improve the flame holder wake flow field. The jet intensity and thermal effect increase with a decrease of the rising edge. As a result, the plasma aerodynamic actuation effect becomes stronger. However, when the rising edge exceeds the optimal value, the cross section of the mainstream decreases significantly due to the high discharge intensity, which makes the growth of the edge velocity of the circulation zone of the flame holder higher than that of the growth in length of the circulation zone, thus the extension effect of the FMRT is reduced.

(4) Effect of install position on aerodynamics actuation

There are complex flow fields behind and inside the flame holder, and the actuator may affect the manipulation of the flow field in the two different installation positions. The actuator was installed on the outside (position 1) and inside surfaces of the flame holder (position 2) to compare the effects on the flow field manipulation. Figure 11 shows the LVA and FMRT curves at different actuation positions, where it was observed that the aerodynamics actuation effect can be achieved regardless of whether the exciter was on the inside or outside surface of the flame holder, but the aerodynamics actuation effect was better when the actuator was installed on the outside surface of the flame holder. At a pressure of 40 kPa, the LVA could be increased by 88.37% and the FMRT by 17.6% at position 1, while the LVA could be increased by 179.5% and the FMRT by 43.5% at position 2. This shows that in the selected air pressure range, the actuator at position 2 had a better effect on flow field manipulation. This may be due to air inlet holes inside the flame holder and a recirculation zone in the flame holder wake. Under the action of a plasma actuator, the internal flow field was disturbed, and the structure of the recirculation zone and vortex changed, thus affecting the wake shedding vortex and recirculation zone of the flame holder. The specific mechanism requires further study.

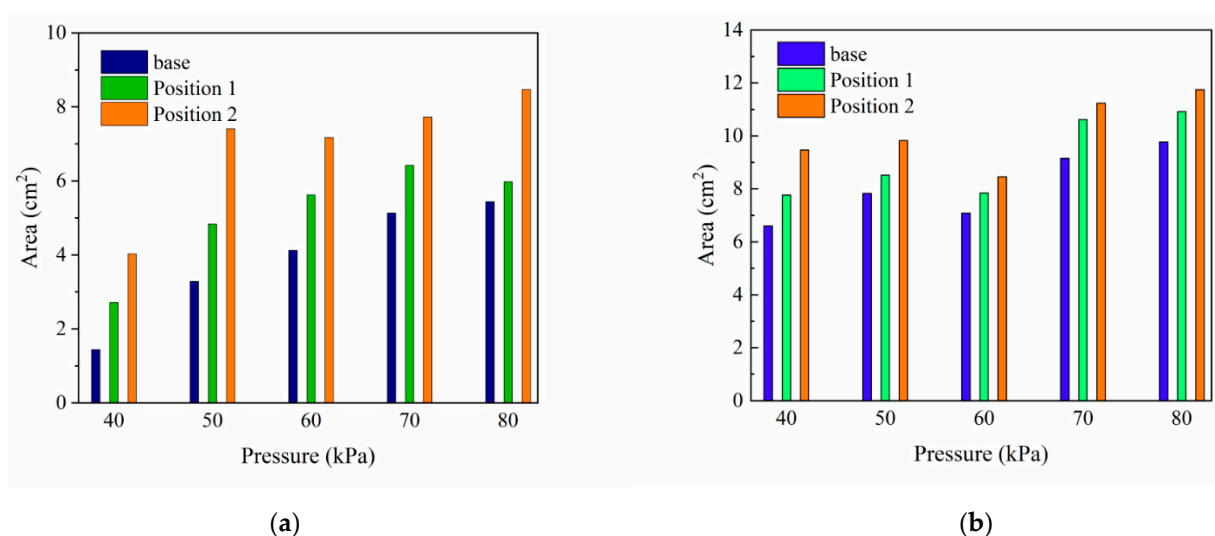


Figure 11. Comparison of the LVA (a) and FMRT (b) to the installation position.

3.3. Ignition Performance of Plasma-Actuated Flame Holder

Based on above flow field characteristics, appropriate excitation parameters and an actuation position (position 2) were selected. Moreover, an ignition experiment was conducted to verify whether the plasma-actuated flame holder could extend the ignition pressure limit. The semiconductor igniter (SI) was installed on the side of the flame holder as the ignition source, as shown in Figure 1. In Figure 12, black line shows the ignition pressure limits of the flame holder without a plasma discharge. It can be seen that the ignition pressure limit decreases with an increase in the total inlet temperature, and that the combustion efficiency increases with an increase in the total inlet flow temperature. the principle of the combustion efficiency measurement method in this paper is to use

isothermal combustion enthalpy difference method to measure. The combustion efficiency is calculated by the following formula:

$$\eta = \frac{C_p T_4^* - C_p T_3^* - f_{AB}(iT_4^* - iT_0^*)}{f_{AB}H_f}$$

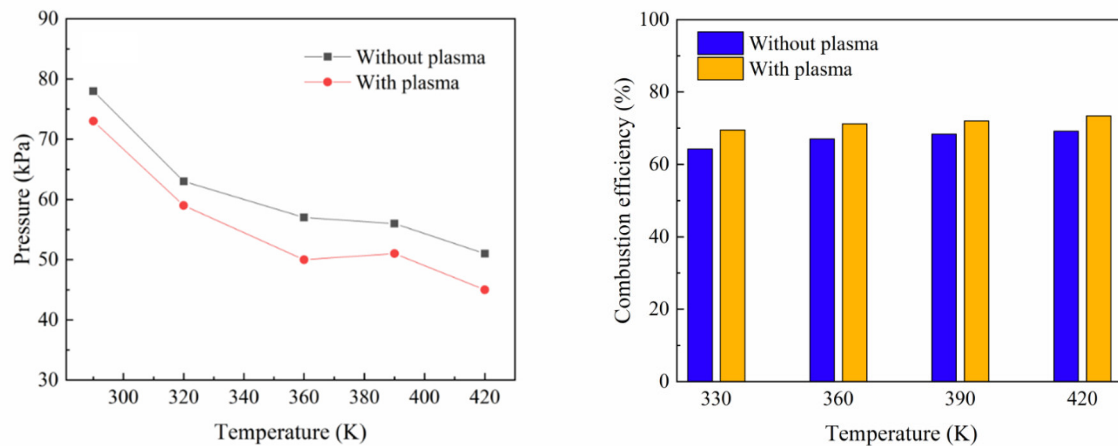


Figure 12. Comparison of the ignition pressure limit and combustion efficiency.

In the formula, $C_p T_4^*$ and $C_p T_3^*$ respectively represent the air enthalpy at the inlet and outlet of the ramjet combustion chamber, iT_4^* and iT_0^* respectively represent the isothermal enthalpy difference at the temperature of T_4^* and 288.16 K. The above values can be found out by the combustion chamber design manual, f_{AB} is the total oil-gas ratio of the ramjet combustion chamber, and η is the calculated combustion efficiency. The exit temperature of the combustion chamber is measured by thermocouple. In the set working condition, after the ignition of the plasma excitation flame holder is successful, the temperature is collected until the combustion is stable. 15 parallel thermocouples were used to measure the temperature, and then the average value was taken to reduce the error and determine the total outlet temperature. The distance between thermocouple and flame holder is 1 m. arranged in three rows along the flow direction, and 5 thermocouples are evenly arranged in each row. The distance between two adjacent thermocouples is 25 mm. The thermocouple adopts B-type double platinum-rhodium thermocouple, which can measure the maximum temperature of 1600 °C for a long time and 1800 °C for short-term use. Using the NI-PXle-4353 module in the NI-PXle-1082 to collect the thermocouple temperature signal, the measurement accuracy is less than or equal to 0.26 °C.

The plasma-actuated flame holder improves the ignition pressure limit and combustion efficiency by 9.12% and 4.3% on average, respectively. At a total inlet temperature of 290 K, the ignition pressure limit was 78 kPa without plasma and 73 kPa with plasma, an increase of 6.5%. At a total inlet temperature of 330 K, the combustion efficiency was 64.2% without plasma and 69.5% with plasma. At a total inlet temperature of 420 K, the ignition pressure limit could be extended by 11.7% from 51 kPa to 45 kPa, and the combustion efficiency increased by 4.4%, from 69.1% to 73.4%. The higher the total inlet temperature, the greater the extension of the ignition pressure limit.

To further explore the ignition performance of the plasma-actuated flame holder, the ignition process was investigated to reveal the ignition mechanism. With and without actuation, the ignition process of the flame holder in the combustion chamber, at $T = 290$ K total inlet temperature, is shown in Figure 13. The breakdown time of the semiconductor igniter is set as the initial moment at $t = 0$. As shown in Figure 13a, the initial flame kernel was generated by the semiconductor igniter without plasma actuator. After 0.7 ms, the initial kernel started to split. At $t = 1.2$ ms, due to gravity, the distribution of the fuel droplet at the lower edge of flame holder was denser than at the upper edge, resulting in the initial flame kernel propagating along the lower edge. At $t = 21$ ms, the flame recirculated into

the recirculation zone and ignited the unburnt fuel–air mixture. The intensity of the flame chemiluminescence increased. At $t = 61$ ms, the flame was stabilized by the flame holder.

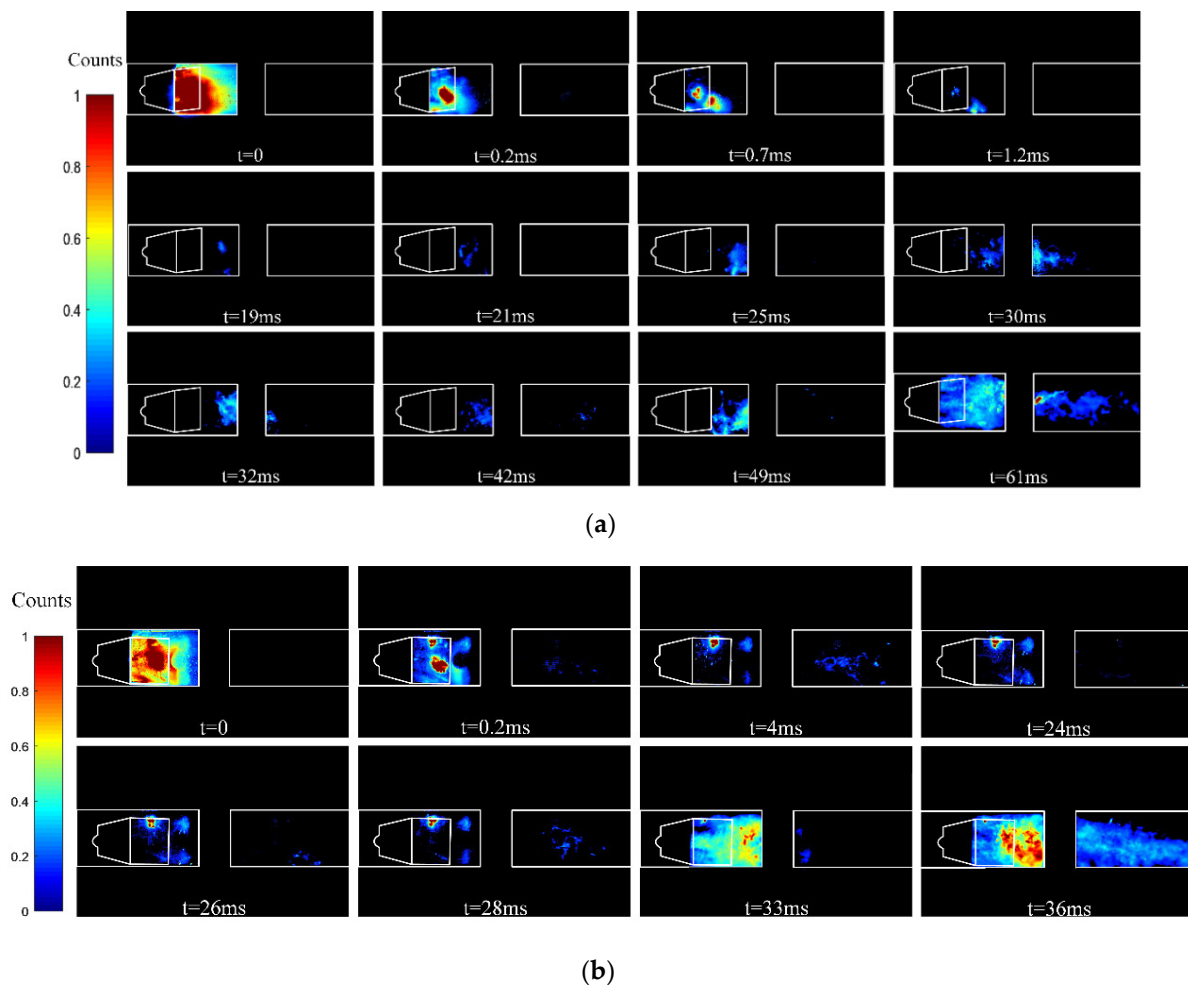


Figure 13. Ignition process in the combustor at $T = 290$ K. (a) without plasma at $P = 80$ kPa; (b) with plasma at $P = 75$ kPa.

Figure 14 shows the pressure in the combustion chamber when the pressure changes. The pressure sensor is located below the combustion chamber and extends into the interior of the combustion chamber. The ignition process of the flame holder with plasma actuation, at $T = 290$ K total inlet temperature, is shown in Figure 13b. At $t = 0.2$ ms, the SI discharged and formed an initial flame kernel. At $t = 4$ ms, the initial flame kernel split into two smaller ones. The upper one was located downstream of the discharge area. The lower one was located in the recirculation zone. From $t = 4$ ms to $t = 28$ ms, as the size of the recirculation zone increased, more fresh air was recirculated from the mainstream and more fuel droplets were recirculated from the inside of the flame holder, resulting in the flame intensity increasing on both, the upper and lower sides. At the same time, it can be observed that the plasma actuator not only increased the size of the recirculation zone, but also continuously deposited heat and radicals into the flame near the discharge region. At $t = 33$ ms, the upper and lower flames combined with each other, and the intensity of the chemiluminescence increased sharply. At $t = 36$ ms, the flame was stabilized by the flame holder. The size of recirculation zone and the recirculation capacity increased with the plasma actuation. In addition, because the energy and radicals were continuously deposited into the flame by the plasma actuator, the ignition delay time was shortened and the flame could be quickly stabilized. In contrast to the pressure evolution curve in the combustor, the time of the flame growth stage was significantly shortened, and the combustion stability

of the stable stage was better, as shown in Figure 14. Figure 14 shows the pressure in the combustion chamber when the pressure changes. The pressure sensor is located below the combustion chamber and extends into the interior of the combustion chamber.

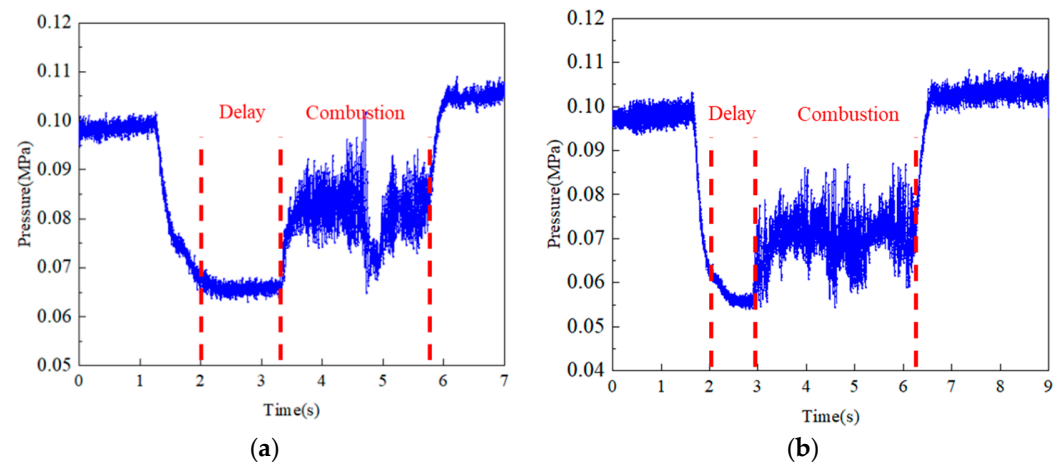


Figure 14. The pressure curve in the combustor. (a) without actuator at $P = 80$ kPa; (b) with actuator at $P = 75$ kPa.

Figure 15a shows the ignition process of the plasma-actuated flame holder without a plasma discharge at a total inlet temperature of $T = 360$ K. As can be seen from the figure, from $t = 0$ to 12 ms, the initial flame kernel which was ignited by SI expanded to the recirculation area. From $t = 15$ ms to $t = 18$ ms, the flame propagated at the downstream position of the recirculation zone. Between $t = 21$ ms and $t = 62$ ms, the flame propagated at the downstream position and recirculated upstream. The recirculation zone continuously ignited the fuel–air mixture, resulting in the continuously increasing intensity of chemiluminescence. At $t = 68$ ms, the flame was stabilized at the upper end of the flame holder.

The ignition process of the flame holder with plasma at a total inlet temperature of $T = 360$ K is shown in Figure 15b. From $t = 0.1$ ms to $t = 20$ ms, the initial flame kernel propagated in the recirculation zone. The plasma actuator continuously discharged and the reacting fuel–air mixture acted as a small pilot heat and radical source. In addition, the intensity of flame chemiluminescence in the recirculation zone was low and scattered. Up until $t = 94$ ms, the flame was stable in the center of the recirculation zone. The image of a stable flame in the combustor is shown in Figure 16.

The ignition process of the flame holder without plasma at a total inlet temperature of $T = 420$ K was captured, as shown in Figure 17a. At $t = 0$ ms, the SI generated the initial flame kernel. From $t = 1$ ms to $t = 12$ ms, the initial flame propagated into the recirculation zone. At $t = 14$ ms, the flame was observed stabilizing in the downstream region and propagating upstream due to the adverse pressure gradient in the recirculation zone. At $t = 16$ ms, the flame intensity rose into the recirculation zone. At $t = 30$ ms, the flame was stable.

As can be seen in Figure 17b, the ignition process of the flame holder with plasma at a total inlet temperature of $T = 420$ K is shown. The initial flame kernel split into two smaller ones, similar to that in Figure 13 at $t = 1$ ms. At $t = 4$ ms, the flame intensity weakened and propagated downstream from the recirculation zone. From $t = 6$ ms to $t = 80$ ms, the flame front went back and forth between the upper and lower sides. The intensity at the upper side was stronger than at the lower side due to plasma actuation. At $t = 90$ ms, stable combustion was established. Figure 18 shows the curve of change in pressure in the combustor. It can be seen that the pressure rises slightly in the combustor with plasma, and that the plasma-actuated flame holder can clearly shorten the ignition delay time.

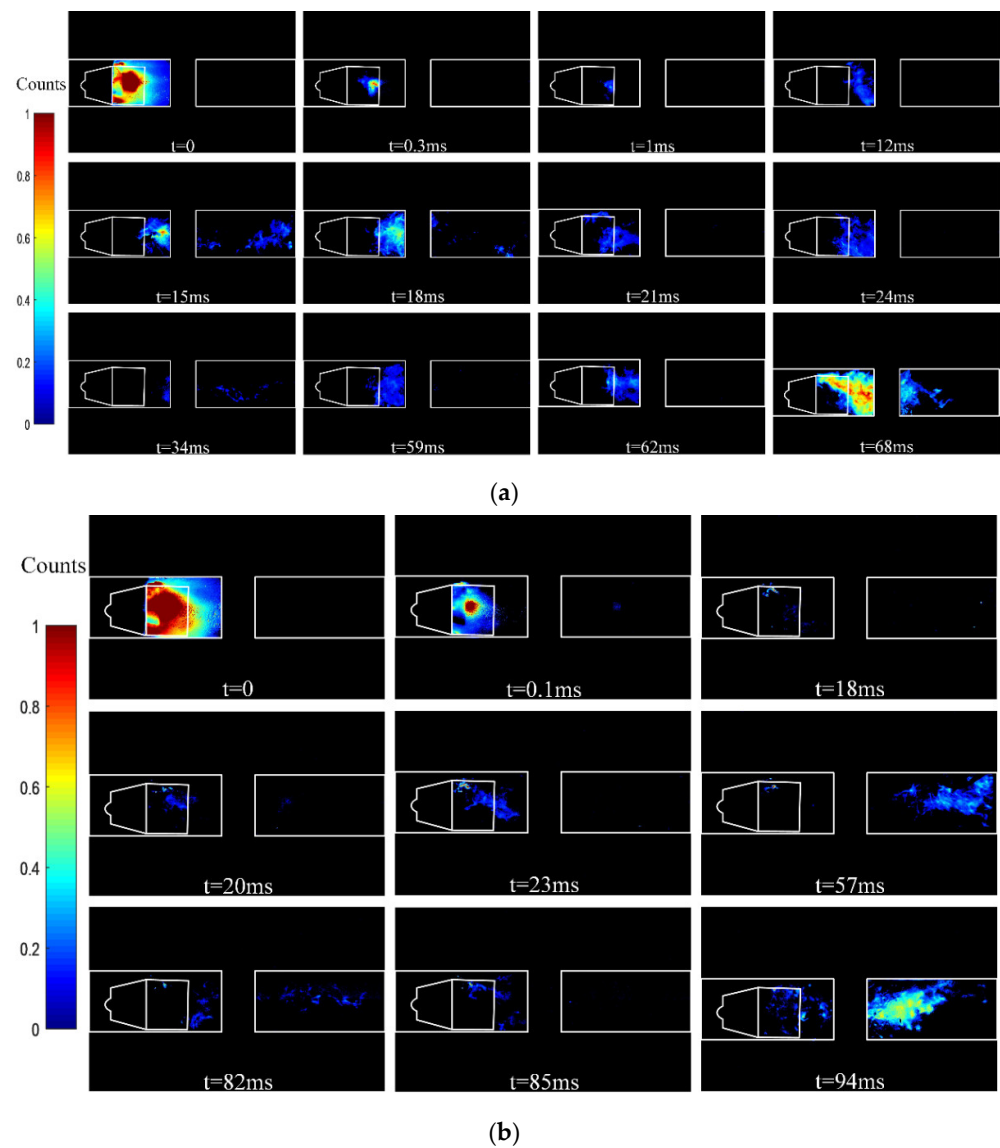


Figure 15. The ignition process in the combustor at $T = 360$ K. (a) without plasma at $P = 62$ kPa; (b) with plasma at $P = 54$ kPa.

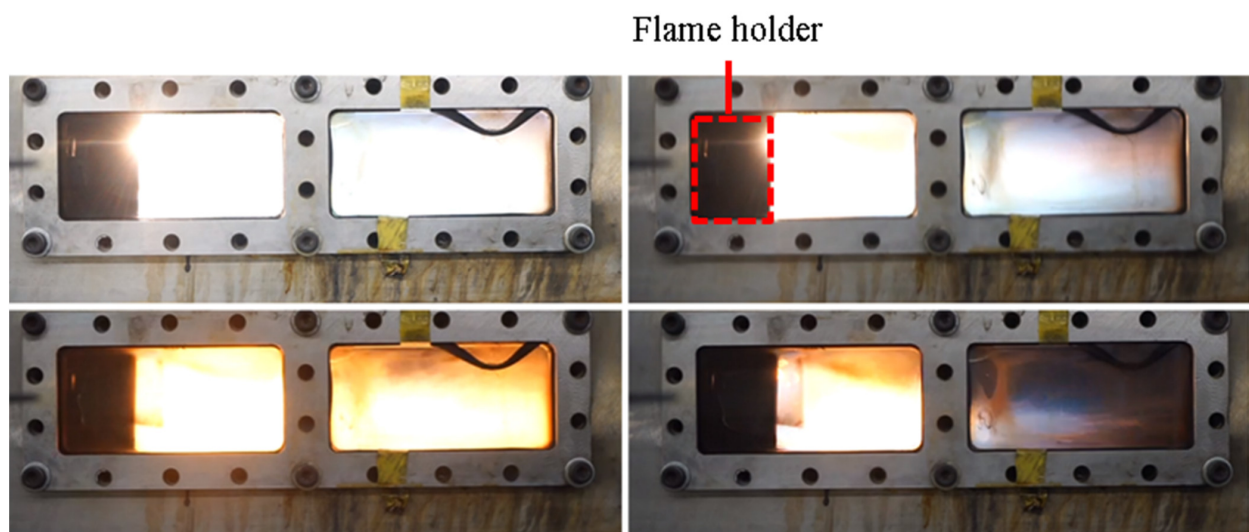


Figure 16. The image of stable flame in the combustor.

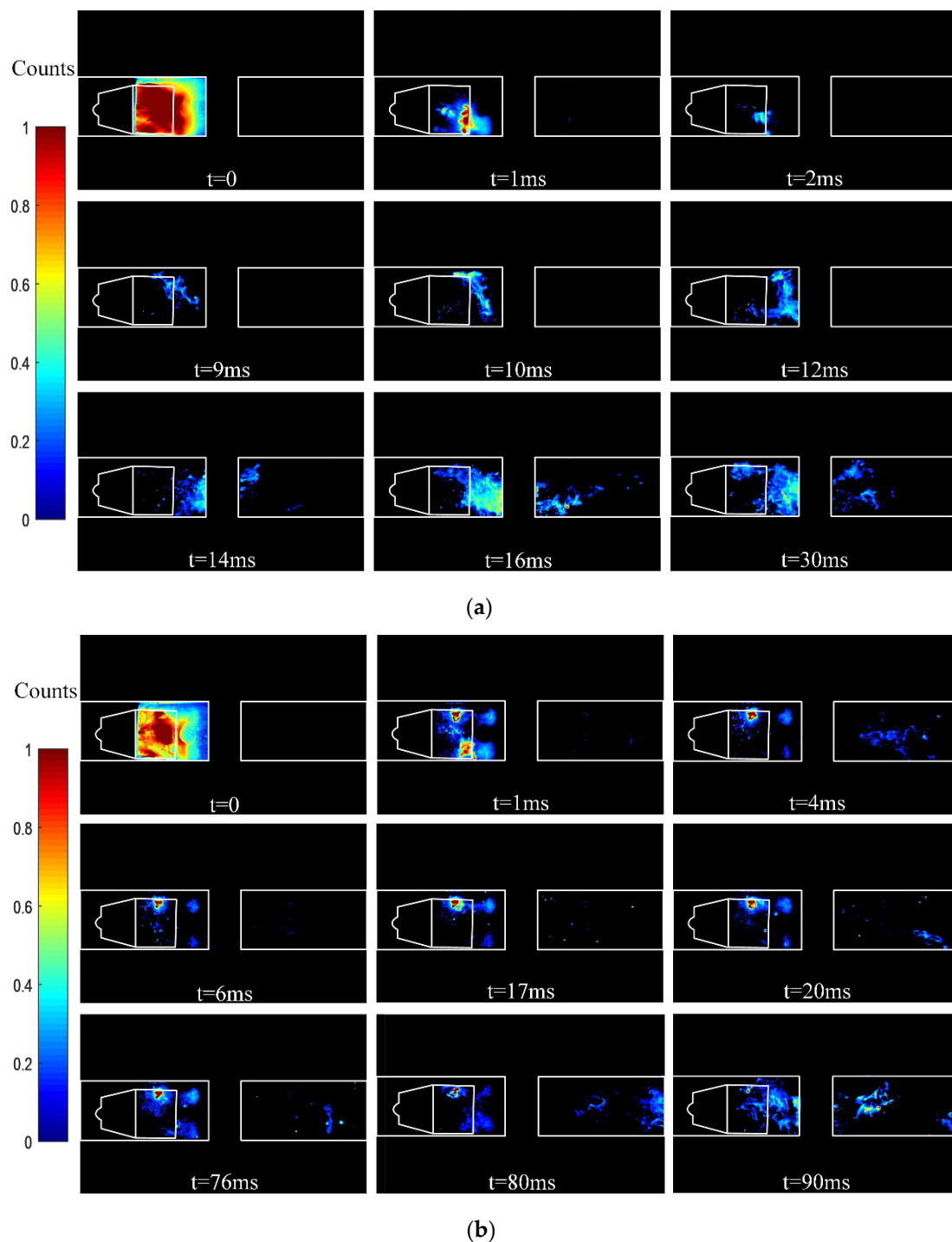


Figure 17. The ignition process in the combustor at $T = 420$ K. (a) without actuator at $P = 54$ kPa; (b) with actuator at $P = 48$ kPa.

By analyzing the ignition process of the plasma-actuated flame holder, the ignition process can be divided into the following three stages. The first stage, also referred to as the ignition delay stage, is when the initial flame kernel is formed by the igniter and continuously propagates. The second stage, also referred to as the recirculation stage, is when the recirculation zone continuously recirculates the mainstream fresh air and atomized fuel from inside the flame holder, causing the burnt gas to constantly reignite the fuel-air mixture, enhancing the flame intensity. The third stage, also referred to as the stable stage, is when the aerodynamic effects of the plasma actuator create a larger recirculation

zone to improve the recirculation cycle. The heat and radicals deposited by the plasma actuator also significantly improve combustion.

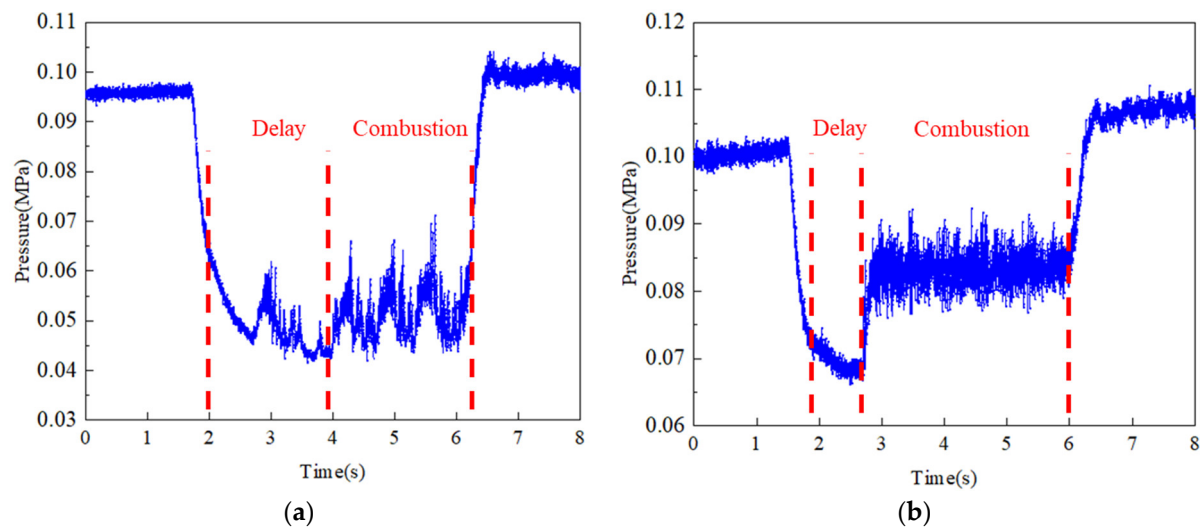


Figure 18. The pressure curve in the combustor. (a) without actuator at $P = 54$ kPa; (b) with actuator at $P = 48$ kPa.

4. Conclusions

In this study, a plasma-actuated flame holder was designed, and the disturbance characteristics of the arc discharge, aerodynamic effects, and ignition process of the flame holder were studied. The conclusions of this paper are as follows:

- 1 The jet direction of the surface arc discharge is vertical upward, and the intensity and shock at low pressures are greater than that at atmospheric pressure. The velocity of the jet dissipates as the pressure decreases. Appropriately increasing the number of surface arc discharge channels will increase the excitation intensity and jet area. Increasing discharge frequencies can increase the height of the jet.
- 2 The experimental results show that 1000 Hz is the optimal frequency for aerodynamics actuation with a pulse width of 5000 ns and rising edge of 500 ns. Microsecond pulse width discharges are better than nanosecond pulse widths. The actuator deploying inside of the flame holder shows better aerodynamic effects than deployment on the outside. At a pressure of 40 kPa, the LVA can be increased by 88.37% and the FMRT can be increased 17.6% with the outside arrangement, but the LVA can be increased by 179.5% and the FMRT can be increased 43.5% using the inside arrangement.
- 3 The ignition pressure limit decreases with an increase of the total inlet temperature, and the combustion efficiency increases with an increase in the total inlet flow temperature. The plasma-actuated flame holder increases the ignition pressure limit and combustion efficiency by 9.12% and 4.3% on average, respectively. The higher the total inlet temperature, the greater the extension of the ignition pressure limit and the smaller the improvement of the combustion efficiency. The plasma-actuated flame holder also significantly shortens the ignition delay time by pressure measurement.

The research in this paper shows that the plasma-actuated flame holder significantly improves the performance of a ramjet combustor.

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