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Experimental study on energy characteristics and ignition performance of recessed multichannel plasma igniter*

Bang-Huang Cai(蔡帮煌), Hui-Min Song(宋慧敏)†, Min Jia(贾敏), Yun Wu(吴云), Wei Cui(崔巍), and Sheng-Fang Huang(黄胜方)

Science and Technology on Plasma Dynamics Laboratory, Air Force Engineering University, Xi'an 710038, *China*

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In the extreme conditions of high altitude, low temperature, low pressure, and high speed, the aircraft engine is prone to flameout and difficult to start secondary ignition, which makes reliable ignition of combustion chamber at high altitude become a worldwide problem. To solve this problem, a kind of multichannel plasma igniter with round cavity is proposed in this paper, the three-channel and five-channel igniters are compared with the traditional ones. The discharge energy of the three igniters was compared based on the electric energy test and the thermal energy test, and ignition experiments was conducted in the simulated high-altitude environment of the component combustion chamber. The results show that the recessed multichannel plasma igniter has higher discharge energy than the conventional spark igniter, which can increase the conversion efficiency of electric energy from 26% to 43%, and the conversion efficiency of thermal energy from 25% to 73%. The recessed multichannel plasma igniter can achieve greater spark penetration depth and excitation area, which both increase with the increase of height. At the same height, the inlet flow helps to increase the penetration depth of the spark. The recessed multichannel plasma igniter can widen the lean ignition boundary, and the maximum enrichment percentage of lean ignition boundary can reach 31%.

Keywords: high altitude extreme condition, recessed multichannel plasma igniter, discharge energy, lean ignition boundary

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1. Introduction

Reliable ignition in the air is an important guarantee for safety and performance of the aeroengine. Extreme conditions such as high altitude, low temperature, low pressure, and high speed will lead to difficulty in secondary starting of the aeroengine.[1] Therefore, improving the secondary ignition capability of the engine is crucial to the safety and development of the engine.[2,3] The problem of insufficient ignition boundary exists in the case of aeroengines at high altitude and on the plaleau, and the conventional ignition system can hardly meet the ignition requirements of engines under such severe conditions.[4]

The rapid formation of a fire kernel which depends on the sufficient ignition energy injected into the combustible mixture, is the key to the success of ignition. If the ignition energy is not sufficient, a fire kernel cannot be formed.[5] The minimum energy exactly required for successful ignition is called the minimum ignition energy (MIE), and the radius corresponding to the fire kernel formed by MIE at the moment of the lowest flame propagation velocity is called the critical fire kernel radius.[6] The critical fire kernel radius is related to the Lewis of the combustible mixture.[7] For macromolecular hydrocarbon fuel, the larger the initial fire kernel is, the wider the ignition boundary of lean oil is achieved.[8] However, under severe conditions such as high altitude, low pressure, and high-speed inlet flow, the critical fire kernel radius will increase, which puts forward higher requirements for the ignition performance under the design conditions of the combustion chamber. Therefore, higher energy, deeper penetration, and larger initial fire kernels are needed to achieve reliable ignition and stable combustion under extreme conditions.

Plasma is a fourth state other than the solid, liquid, and gaseous states of matter.[9] At present, as plasma ignition has the advantages of short ignition delay, strong flame penetration, and large ignition energy, can enhance combustion while ignition, it has been paid more and more attention in recent years, and this new ignition technology has been widely applied in aviation industry.[10–12] The mechanism and application of plasma ignition have been extensively studied and many representative results have been obtained. Wolk[13] compared the performance of microwave plasma ignition and traditional spark ignition under different pressure, and equivalent ratio conditions in constant volume incendiary bombs, and found that the effective energy injected kernel of microwave discharge was larger, and the ignition delay time was greatly shortened. Kim[14] found that as the air-C3H8 equivalence rates, the progressive combustion and reaction by the arc and jet plasma discharges are more improved than the conventional spark discharge in a rarefied condition. Lance S Jacobsen's research showed that plasma igniters can produce 5000 K of high-temperature active gas.[15] Mosbach[16] described stable combustion flames with two different fuel air

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†Corresponding author. E-mail: min_cargi@sina.com

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ratios and mass flow through the distribution characteristics of kerosene, OH, and soot luminosity. Leonov[17,18] found that the sliding arc discharge plasma has a large-area ignition ability, which can shorten the ignition delay time of N-heptane by 500 μs. Hnatiuc[19] proposed a dual-spark ignition system, which generated higher ignition energy and larger discharge area than traditional igniters. Briggs[20] compared several ignition methods, including multi-electrode ignition, and the results showed that it is of great significance to produce a large number of effective flame kernel and long-life kernel under the condition of lean combustion. Wang[21] studied the electrical and plasma characteristics of radio frequency (RF) discharge plasma under variable pressure, the results showed that the charging voltage Lissajous curve changes and the discharge energy increases with the increase of the pressure. Zhang[22] proposed a new multichannel spark discharge analysis model and found that with the increase of input voltage and the decrease of breakdown voltage, the increase of maximum discharge channels is almost linear. Huang used a single ignition power supply to drive multiple plasma igniters, and found that the energy efficiency of the ignition power supply increased with the number of igniters.[23]

Conventional spark igniters have only one discharge channel, so the heating effect is limited, the discharge energy is not enough, the spark penetration depth is small, and the initial kernel size is small. Therefore, a new kind of igniter is urgently needed. Under the premise of keeping the ignition power supply unchanged, it can improve the energy utilization rate of the original ignition of low temperature, low pressure, and high speed, so as to improve the secondary ignition capacity at high altitude.

In this paper, a multichannel plasma igniter with a round cavity is proposed, which aims to rapidly eject the arc through the high-temperature air in the cavity, so as to make the discharge energy more concentrated. Three-channel and five-channel configurations were adopted and compared with conventional spark igniters in the experiment. Firstly, the spark energy of three kinds of igniters is measured by electric energy measurement and thermal energy measurement under normal pressure, and the conversion efficiency of electric energy and thermal energy is calculated. Then, the spark discharge images of three igniters with or without incoming flow were taken at different heights, the influence of height and incoming flow on the penetration depth of igniters was studied. Finally, the ignition experiments of aviation RP-3 kerosene were carried out in the component combustion chamber at different heights, the lean ignition boundary of three igniters was studied.

2. Experimental equipment

2.1. Conventional spark igniter and recessed multichannel plasma igniter

Two kinds of igniters were used for comparison in the experiment. One was a conventional spark igniter (SI), as shown in Fig. 1. The middle circular electrode is the high voltage electrode of the igniter, and the outer ring electrode is the grounded electrode. The ceramic insulator is between the high voltage electrode and the grounded electrode. The outer diameter of the central electrode is 7 mm, the outer diameter of the grounded electrode is 20 mm, and the inner diameter is 9 mm. To reduce the breakdown voltage of spark discharge, a layer of 1-mm wide silicon carbide is painted to the insulator between the high voltage electrode and the ground electrode near the surface to a depth of 2 mm. Another igniter is a self-designed recessed multichannel plasma igniter (RMPI), including three-channels and five-channels configurations, as shown in Fig. 2. The head of the igniter is made of alumina ceramics, and the outer diameter of the main part of the ceramic is 14 mm. In order to avoid creeping between the electrode and the combustion chamber, the diameter of the processed ceramic head is 12 mm, the height is 2 mm, and then the shell of the igniter is assembled with the outer diameter of 20 mm. A circular cavity with an inner diameter of 9 mm and a depth of 5 mm is designed on the ceramic. Four or six cylindrical electrodes with a diameter of 1.5 mm are installed in the cavity, respectively, the electrode spacing is 3.4 mm. A layer of silicon carbide is coated between the electrodes to reduce the breakdown voltage, the electrode is close to the inner wall of the round cavity and arranged in a circumferential manner in the concave cavity.

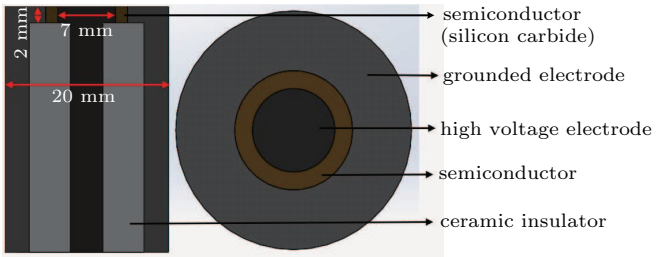


Fig. 1. Conventional spark igniter.

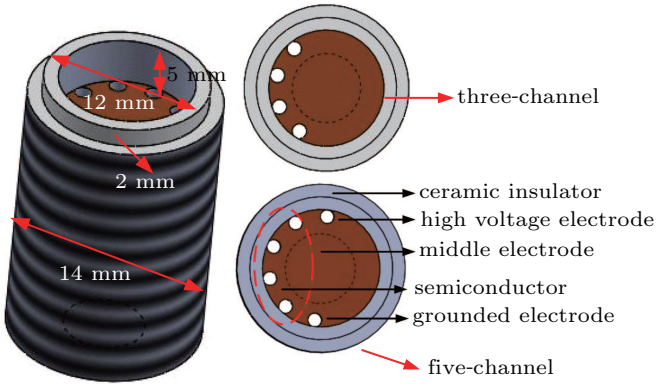


Fig. 2. Recessed multichannel plasma igniter.

2.2. Energy testing system

The electric energy and thermal energy measurement methods are important means to measure the spark energy of

the igniter of the aviation gas turbine engine. The two energy test systems are shown in Fig. 3.

2.2.1. Electrical energy testing system

As shown in figure 3, the electrical energy testing system includes a plasma ignition power supply, a digital oscilloscope (Tektronix DPO4104), a high voltage probe (Tektronix P6015 A, it can measure 20-kV DC voltage and 40-kV pulse, time cycle is 100 ms, bandwidth is 75 MHz) and a current loop (Pearson 6600, the sensitivity is 0.1 V/A, the aperture is 2 inches (1 inch = 2.54 cm), the maximum peak current is 2 kA, and the drop rate is 15% per nanosecond) and some high voltage wires. The operating frequency of the plasma ignition power supply is about 2 Hz–3 Hz, the positive and negative peaking value of the output voltage is greater than 12 kV, and the rated energy storage of a single discharge pulse is 20 J, providing the input electric energy for the ignition system. When the igniter discharges, the discharge voltage and current of the igniter are measured by a high voltage probe and a current loop, and the voltage and current signals are recorded by a digital oscilloscope.

2.2.2. Thermal energy testing system

As shown in Fig. 3, the igniter is connected with the $M20 \times 1.25$ internal thread of the temperature-measuring chamber through the external thread of $M20 \times 1.25$, and the connection is sealed with high-temperature resistant silica gel to ensure that the chamber is sealed. The temperature–capacity cavity is a stainless steel cylindrical sleeve with a thickness of 1 mm and a total length of 10 cm. The other end of the sleeve is provided with an internal thread of $M8 \times 1.25$, which is connected to the external thread of the K-type probe thermocouple (WTNT-187, measuring range 0 ℃–800 ℃). The effective distance between the thermocouple and the igniter head is 7 cm, and the real-time air temperature measured by the thermocouple is displayed by the TM902C digital display thermometer.

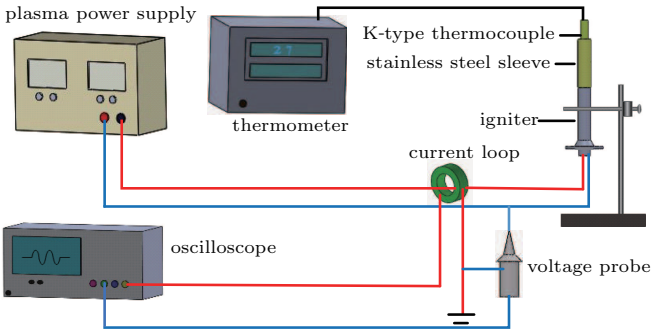


Fig. 3. Energy testing system.

2.3. High-altitude environment simulation testing system

The kernel components of the high-altitude environment simulation test system mainly include screw air compressor, air storage tank, filter, combined dryer, cool air generator, component combustion chamber, exhaust chamber, vacuum pump, cooling tower, solenoid valve, and manual valve, as shown in Fig. 4. Among them, the screw air compressor produces high pressure air, which is stabilized by the gas storage tank to supply the system. Simulate the low-pressure environment for experiments by working the vacuum pump and adjusting the opening of the relevant valve. The cooling tower provides cooling circulating water to ensure the normal operation of the vacuum pump. The component combustion chamber is a twin-head swirl combustion chamber, the size is the same as the actual size of the aeroengine. The igniter is installed between the two heads, which can simulate the ignition environment of the engine in the real situation.

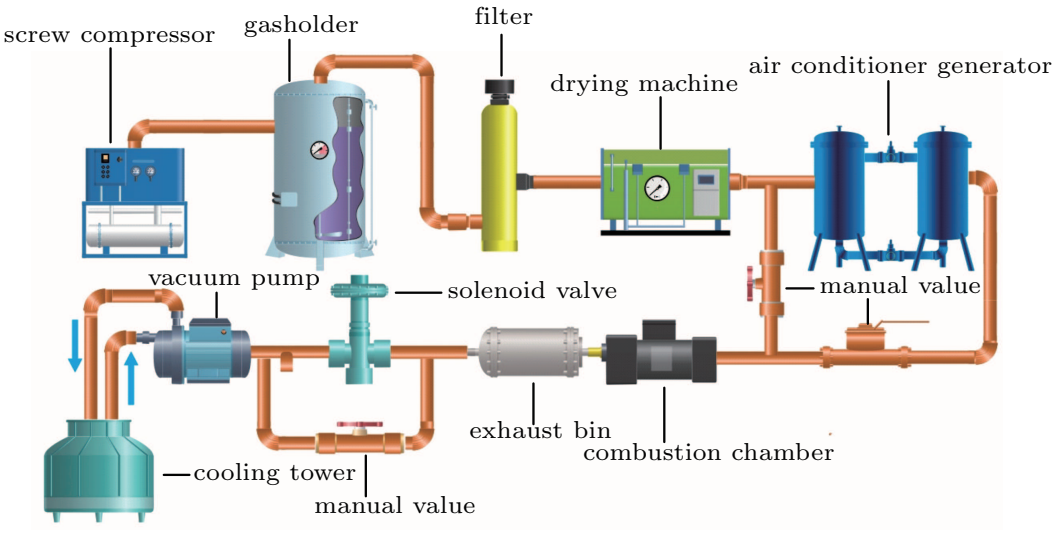


Fig. 4. High-altitude environment simulation testing system.

3. Results and discussion

3.1. Energy characteristics of recessed multichannel plasma igniter

Energy characteristic is one of the most important characteristics of plasma igniter. For the ignition power supply with fixed energy storage, the measurement of spark discharge energy is an important parameter and basis to study and judge the performance of the igniter.

3.1.1. Electrical characteristics of plasma igniter

The electric energy measurement method mainly measures the voltage, current, and spark frequency of the electrode when the spark is generated by the igniter. After formula conversion, the energy of the spark is determined. The conversion efficiency of the igniter is obtained by calculating the ratio of the electric energy produced by the igniter to the output electric energy of the ignition system. In this paper, discharge waveforms of conventional SI and RMPI were measured under normal pressure, as shown in Fig. 5.

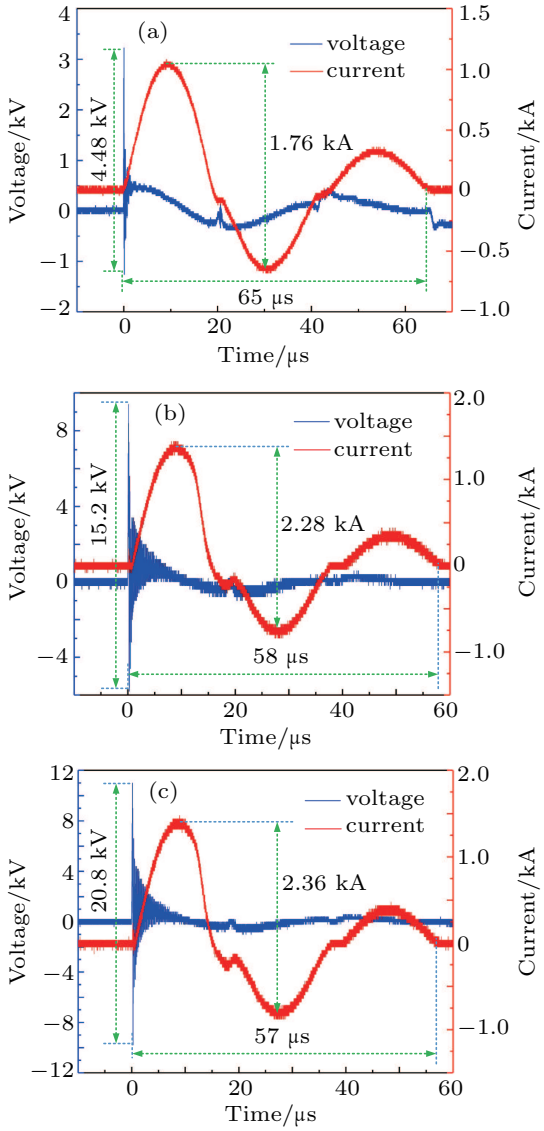


Fig. 5. Discharge waveform of igniter (a) conventional spark igniter, (b) recessed three-channel plasma igniter, (c) recessed five-channel plasma igniter.

It can be seen from the voltage and current waveform that the breakdown voltage of the RMPI is significantly higher than that of the CSI, the breakdown voltage of CSI is 3.23 kV, the three-channel plasma igniter is 9.45 kV, and the five-channel plasma igniter is 10.94 kV. Obviously, the breakdown voltage of RMPI is larger. After breakdown, the voltage amplitude rapidly oscillates and the current value rises to the peak value of 1.4 kA, and then begins to oscillate and decay. The current of the RMPI is obviously higher than that of the CSI. The peak-to-peak value of the CSI was only 1.76 kA, while the peak-to-peak value of the three-channel plasma igniter was 2.28 kA, nearly 30% higher than that of the CSI. The peak-to-peak value of the five-channel plasma igniter was 2.36 kA, 34% higher. The discharge duration of the RMPI is relatively short, 58 μs and 57 μs respectively, compared with 65 μs for the CSI. This is because the discharge of the CSI is the breakdown of the wall of the central anode and the lateral ground electrode, and the discharge channel is shorter, while the discharge electrode of the RMPI is arranged and distributed along the c-shape circumference, and the discharge channel is longer, the equivalent impedance during breakdown is larger, and the discharge energy is released faster. The electric energy consumed in the igniter discharge gap during a discharge and the conversion efficiency of electric energy are calculated by measuring the time integral of voltage and current. The calculation formula is as follows:

$$W_{\mathrm{do}} = \int_0^T U(t)I(t)\mathrm{d}t, \tag{1}$$

$$\eta = W_{\mathrm{do}}/W_{\mathrm{di}}. \tag{2}$$

Among them, W_{do} is the value of single discharge energy in unit joule (J); W_{di} is the output power of the power supply in unit joule (J); $U(t)$ is the value of the discharge voltage in unit volts (V); $I(t)$ is the value of the discharge current in unit amperes (A); T is the value of spark duration in unit seconds (s); η is the energy conversion efficiency.

In order to avoid inaccurate measurement of single spark energy, five discharge energies were measured for each igniter in the experiment, and the average value was taken to obtain the calculated results of discharge cycle energy and energy conversion efficiency of the three igniters, as shown in Fig. 6. As can be seen from the figure, the spark discharge energy of the RMPI is significantly higher than that of the CSI in one cycle, and the five-channel igniter has a higher discharge energy than the three-channel igniter. The discharge cycle energy of CSI is 5.2 J, and the electric energy conversion efficiency is 26%. While discharge energy of three-channel plasma igniter is 7 J, and the electric energy conversion efficiency is increased from 26% to 35%. The discharge energy of five-channel plasma igniter is further increased to 8.6 J, and the electric energy conversion efficiency is increased from 26% to 43%.

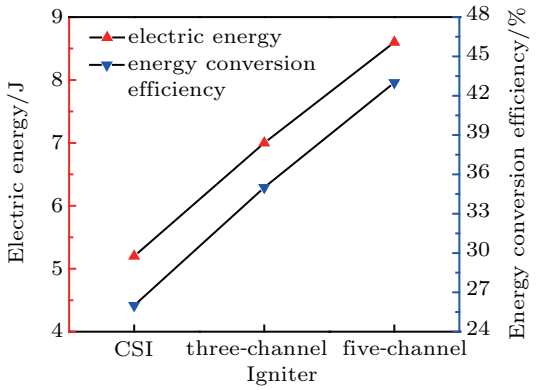


Fig. 6. Comparison of the discharge energy and conversion efficiency.

The spark discharge can be divided into three stages: breakdown stage, arc stage and glow stage.[24] Under high voltage, the electrode begins to break down, the voltage drops, and the current increases. The period of this stage is relatively short, only a few microseconds. After the current channel is formed, the current begins to oscillate and decay, and the discharge enters the arc stage. At the end of the discharge, the discharge enters the glow stage, the voltage and current begin to drop until zero, and the spark disappears. The formation and maintenance of the spark are mainly in breakdown stage and arc stage, while the energy released by the discharge is the most efficient in breakdown stage. Although the discharge duration of the CSI is longer, the discharge duration of CSI is longer. But it can be seen from Figs. 1 and 2 and the size description of the igniter that the electrodes of the RMPI are c-shaped, with larger electrode spacing and more discharge channels, thus making the total breakdown impedance larger. However, there is only silicon carbide with a thickness of 1 mm between the high voltage electrode and the ground electrode of the CSI, and the discharge channel is shorter, the breakdown impedance and voltage are smaller, and the breakdown is relatively easier. Therefore, the breakdown stage is short, making the spark discharge quickly enters the discharge stage and glow stage. The current intensity of glow discharge is small and the effective utilization rate of energy is low. However, the breakdown stage of the discharge of the RMPI takes longer, the length of the discharge channel increases significantly, and the breakdown impedance increases, resulting in higher breakdown voltage, larger arc current, more energy released, and higher discharge efficiency.

3.1.2. Thermal characteristics of plasma igniter

The thermal energy measurement method mainly measures the change value of the air temperature change in the corresponding closed space when the igniter produces sparks, and determines the actual thermal energy generated by the igniter spark through formula calculation. By calculating the ratio between the thermal energy generated by the spark and the discharge electric energy, the efficiency of the conversion of electric energy into heat energy is obtained. Studies have shown that only a small part of the energy released by the discharge of the igniter is injected into the fire kernel for heating the oil and gas mixture,[25] and the effective utilization of this part of energy cannot be accurately measured. The method of calculating the heat energy and thermal energy conversion efficiency by measuring the air temperature in the igniter discharge heating zone is not accurate, but it can be used to analyze and characterize the performance of the igniter to some extent.

The heat transfer process by which a high-temperature fluid transfers heat to a cryogenic fluid on the other side through a solid wall is called the total heat transfer process, or the heat transfer process for short. The process of heat passing through a solid wall is purely as heat conduction, and the transfer of heat due to the temperature difference between the fluid and the surface in contact is called convective heat transfer. The heat transfer inside the stainless steel sleeve is heat conduction, while the heat transfer from the outer wall surface to the outside atmosphere is the composite surface heat transfer of convection and radiation. Heat radiation is generally the radiation between solids. Liquid and gas can also transfer energy in the form of radiation, but it accounts for a very small part of the total transfer. At the same time, the heat radiation can only become the main heat transfer mode at high temperature. According to the temperature change curve, the temperature field changes little in the experiment, and the convection heat transfer coefficient of stainless steel remains unchanged basically within the range of temperature change, and only the heat released by the spark in the sleeve, no other heat source, the heat transfer is relatively uniform. Therefore, the thermal radiation can be ignored, and the experimental heat transfer process is simplified. Thus the heat flow in each link of the overall heat transfer is the same, that is, the heat conduction in the stainless steel sleeve is the same as the heat transfer between the outer wall and the atmosphere. In the experiment or engineering practice, the wall temperature is often unknown, and it is also difficult to accurately measure, so it is very inconvenient to directly use the Fourier formula or Newton cooling formula, while the fluid temperature is relatively easy to measure. Therefore, in this experiment, considering that the temperature of the inner wall of the stainless steel sleeve is consistent with the temperature of the air inside the cavity, the heat transfer is calculated according to the forced convection heat transfer equation between the outer wall of the stainless steel and the outside air

$$\Phi = KA\Delta T. \tag{3}$$

When the temperature in the cavity is T at time t, the heat absorbed by the air in the cavity and the stainless steel sleeve is

$$\begin{aligned} Q &= C_1 m_1 (T - T_0) + C_v m_v (T - T_0) \\ &= (C_1 m_1 + C_v m_v)(T - T_0). \end{aligned} \tag{4}$$

The heat released by the igniter is the sum of the heat absorbed by the air in the chamber and the stainless steel sleeve and the heat transferred between the outside wall and the outside air, namely,

$$Pt = (C_1 m_1 + C_v m_v)(T - T_0) + KA(T - T_0). \tag{5}$$

The first order nonlinear homogeneous equation is obtained by taking the differential of both sides of Eq. (5),

$$(C_1 m_1 + C_v m_v)\frac{\mathrm{d}(T - T_0)}{\mathrm{d}t} = P - KA(T - T_0). \tag{6}$$

The analytical solution of Eq. (6) is

$$T_t = \frac{P}{KA}\left[1 - \exp\left(-\frac{KA}{C_1 m_1 + C_v m_v}t\right)\right] + T_0. \tag{7}$$

Among them, T_0 is the initial temperature and the unit is K; Φ is the heat flow through area A in unit time, in unit W; K is the convective heat transfer coefficient of 304 stainless steel, in units of W/(m^2·K); A is the surface area of the stainless steel sleeve wall; P is the heating power of the igniter, and the unit is W; C_1 is the specific heat capacity of 304 stainless steel at constant volume in units J/(kg ·K); m_1 is the mass of the stainless steel sleeve in unit kg; C_v is the specific heat capacity of air at constant volume in units of J/(kg ·K); m_v is the air mass in the cavity in units of kg; t is the discharge time in units of s.

The experimental recorded the change of air temperature within 40 s after discharge with time in the airtight temperature-measuring cavity, as shown in Fig. 7. The initial temperature in the cavity is 295 K. With the increase of discharge time, the air temperature in the cavity keeps rising. About 30 s after the discharge, the air temperature in the cavity of the three kinds of igniters tends to be stable, reaching the thermal equilibrium state.

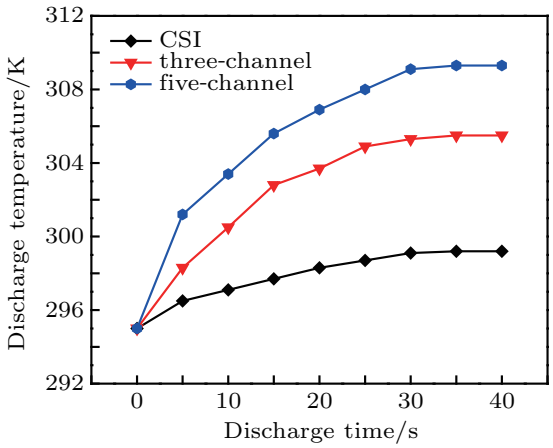


Fig. 7. Air temperature change in the discharge chamber.

Since the temperature-measuring chamber of the igniter is a airtight space, the temperature inside the chamber varies between 295 K and 310 K, the change range has little influence on the specific heat capacity of air at constant volume, which can be ignored. The specific heat capacity of air at constant volume at room temperature is 0.717 kJ/(kg ·K), the air density at room temperature and pressure is 1.29 kg/m, the inner diameter of stainless steel cylindrical sleeve is 1 cm, the effective length is 5 cm, and the air mass in the temperature measurement chamber is 2.84×10^{-5} kg. Put the data into the formula and calculate the analytical solution equation of the three igniters. By analyzing and fitting the heating power of the three igniters, the thermal energy generated by the igniters and thermal energy conversion efficiency is calculated respectively according to Eqs. (8) and (9):

$$W_{\mathrm{di}} = \frac{Pt}{f}, \tag{8}$$

$$\eta_r = W_{\mathrm{ro}}/W_{\mathrm{di}}, \tag{9}$$

where, W_{ro} is the output heat energy of the igniter, and the unit is J; f is the discharge frequency of the igniter in unit Hz; W_{di} is the single discharge energy of the igniter, and the unit is J; η_r is the efficiency of converting electric energy into heat energy.

The output thermal energy and conversion efficiency of the three igniters can be calculated as shown in Fig. 8. As can be seen from the figure, the output thermal energy of CSI is 1.3 J, and the conversion efficiency of thermal energy is 25%. The output thermal energy of the three-channel plasma igniter is 3.6 J, and the conversion efficiency of thermal energy is increased from 25% to 51%. The output thermal energy of five-channel plasma igniter is 6.2 J, and the conversion efficiency of thermal energy is increased from 25% to 73%, which is more obvious. For the RMPI, the discharge current is large, and the heating power for the air medium around the electrode is larger. Therefore, it has greater heat energy and higher heat energy conversion efficiency.

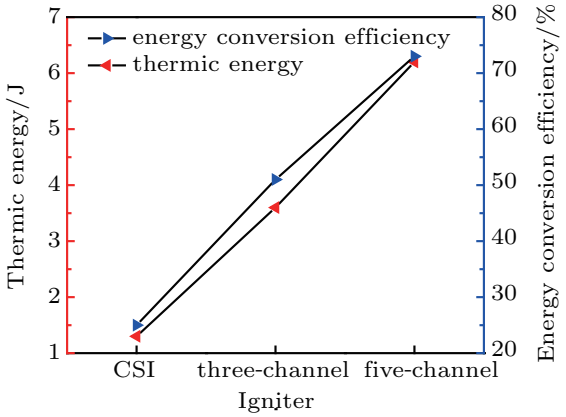


Fig. 8. The comparison of the output thermal energy and the thermal energy conversion efficiency.

3.2. Characteristics of spark plasma evolution

In order to study the evolution characteristics of spark plasma of the igniter under the extreme conditions of high altitude, experiments were conducted in the component combustion chamber of high-altitude environment simulation bench. After simulating the conditions of the combustor on the ground

and the low-pressure state at an altitude of 4 km–16 km, the characteristics of spark plasma evolution of three igniters at different heights were photographed by a high-speed camera. Set the resolution of the high-speed camera to 512×320, the frame rate to 10^5 pps, and the exposure time to 4.545 μs.

3.2.1. Spark penetration depth

The spark penetration depth is the basis and key parameter of spark plasma evolution characteristics. Increasing the penetration depth of the spark can shorten the ignition delay time and achieve fast ignition. The effects of different heights, number of discharge channels and the presence of incoming flow on the penetration depth of igniter were measured and compared.

Figure 9(a) shows the evolution law of spark penetration depth under conditions of no incoming flow and different heights. As can be seen from the figure, with the increase of height, and the penetration depth of the spark increases gradually. From the ground state to the height of 8 km, the spark penetration depth of the RMPI is higher than that of the CSI, and after the height reaches 10 km, the spark penetration depth of the CSI is higher than that of RMPI. The penetration depth of the five-channel plasma igniter is obviously higher than that of the three-channel plasma igniter, it can be inferred that the increase of the number of channels in a certain range is beneficial to increase the penetration depth of the spark.

After applying the incoming flow, the spark penetration depth of the three igniters is shown in Fig. 9(b). The spark penetration depth of the three igniters increases gradually with the increase of the height. In the range of 0 km–8 km, compared with CSI, the spark penetration depth of RMPI is significantly greater. With the increase of the height, the increase rate of the spark penetration depth of CSI is larger, exceeding that of RMPI after the height of 10 km, and the penetration effect is better.

Under the condition of with or without incoming flow, the change trend of igniter's penetration depth is basically the same, the advantage of RMPI is obvious at 0 km–8 km. This is because when the height is smaller, the breakdown voltage and discharge energy of the RMPI are larger. On the one hand, the air around the electrode is affected by thermal compression and magnetic compression effect of the electric spark. On the other hand, constrained by the volume of the cavity wall of the igniter, the interaction of gas molecules intensify, the collision intensify and the kinetic energy of gas molecules increases, so that the electric spark with the release of heat are ejected from the cavity, eventually results in a larger penetration depth. However, when the altitude is greater than 8 km, on the one hand, the breakdown voltage of the igniter drop and the discharge energy decreases as the air becomes thinner and the air pressure decreases. On the other hand, as the discharge current decreases correspondingly, the heating power decreases, and the heating area decreases, the thermal compression effect of the air around the electrode weakens, and the outward radiation heat decreases. The final result is that the penetration depth of the spark ejected from the 5-mm cavity decreases, while the discharge of the CSI occurs on the surface of the igniter head, and the increase of the height has relatively little effect on the penetration depth of the spark. Therefore, at higher altitudes, the spark penetration of CSI is greater than RMPI relatively.

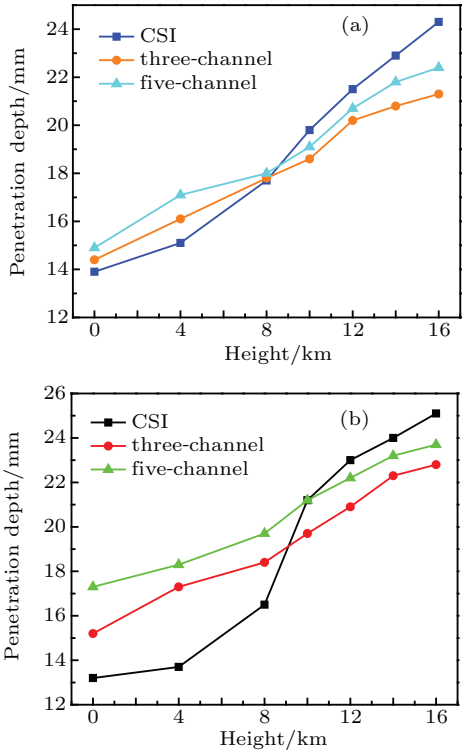


Fig. 9. Penetration depth of spark at different heights (a) no incoming flow, (b) incoming flow.

In the actual flight environment, the higher the altitude of the aircraft, the smaller the intake flow of the combustion chamber. In order to study the influence law of incoming flow on igniter's spark characteristics, the spark penetration depth of RMPI at different heights and with or without incoming flow was compared, as shown in Fig. 10. Figure 10(a) shows the spark penetration depth of the three-channel plasma igniter, and figure 10(b) shows the spark penetration depth of the five-channel plasma igniter. It is obvious from the figure that under the condition of incoming flow, the spark penetration depth of the two kinds of multi-channel plasma igniters is greater than that without incoming flow. This is because with the increase of the height, the inlet flow velocity of the combustion chamber increases, the turbulence pulsation of the flow field around the spark increases, and the aerodynamic force perpendicular to the penetration direction of the spark increases, so that the spark is drawn along the downstream direction of the flow. The greater the velocity of the incoming flow, the greater the penetration depth. Therefore, the air inflow helps to increase the penetration depth of RMPI.

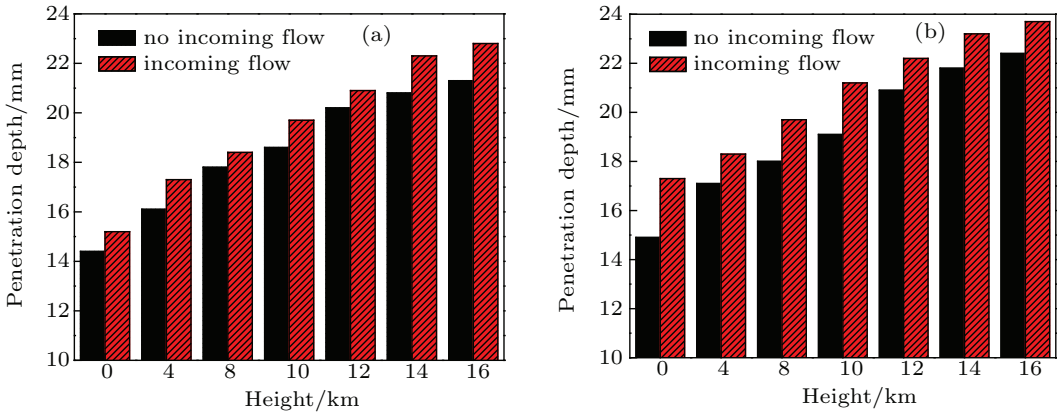


Fig. 10. Comparison of the penetration depth of RMPI with or without incoming flow: (a) three-channel, (b) five-channel.

3.2.2. Excitation area

Excitation area is another important characteristic parameter of spark plasma evolution. The probability of successful ignition is closely related to the excitation area. The larger the excitation area, the easier it is to achieve successful ignition. The discharge spark images under ground and high-altitude conditions were taken, and this paper selected the maximum brightness moments of three igniters at different heights, as shown in Fig. 11.

Set the same light intensity threshold, analyze and calculate the excitation area of three kinds of igniters at different heights, as shown in Fig. 12. From the ground state to the height of 8 km, the area of the excitation area of the three igniters is not much different, and the RMPI has a slight advantage. With the increase of height, the increase rate of five-channel plasma igniter is fast, while that of three-channel plasma igniter and CSI is slow. This is because the discharge intensity of the five-channel plasma igniter is large and the conversion efficiency of electric energy and heat energy is high, it produced bright spark discharge after discharge channel breakdown, which quickly produces a large amount of high-temperature gas around the arc, thus making the excitation area larger. By analyzing and comparing the excitation area of the three types of igniters, the recessed five-channel plasma igniter has the largest excitation area, which can increase the contact area with the combustible mixture in the combustion chamber, improve the ignition probability, and have the potential for successful secondary ignition under extreme conditions.

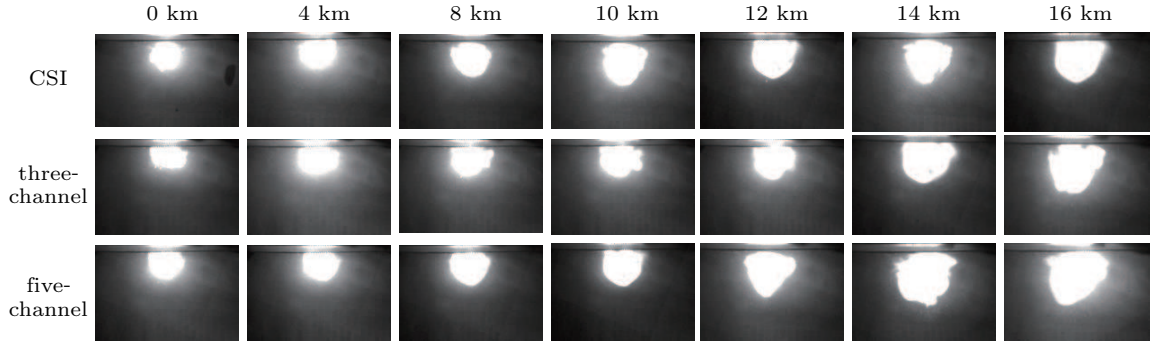


Fig. 11. Change of excitation area of three igniters at different heights.

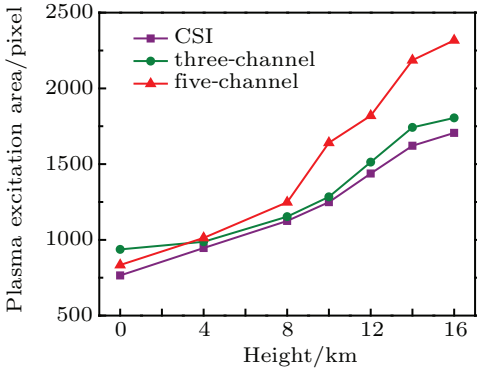


Fig. 12. Change of excitation area.

3.3. Ignition performance of plasma igniter

According to the experimental results of energy characteristics and spark plasma evolution characteristics, the RMPI has higher ignition energy and energy conversion efficiency than CSI, and has certain advantages in penetration depth and plasma excitation area, which is expected to widen the ignition boundary of lean oil.

In order to study the difference in ignition performance between CSI and RMPI under normal pressure, the experimental image of the ignition process of the two igniters under ground condition at the lean ignition boundary was captured,

as shown in Fig. 13. The resolution of the high-speed camera is 512×384, the frame frequency is 8×10^4 fps, the exposure time is 3.9 μs, the fuel flow of the CSI is 3 g/s, the fuel flow of the RMPI is 2.5 g/s, and the inlet flow is 100 g/s. It is obvious that the ignition delay of recessed five-channel plasma igniter is smaller and the flame development is faster, so it is more capable of achieving fast and reliable ignition.

The high-altitude environment simulation experiment bench was used to simulate the extreme conditions from ground state to 16-km high-altitude. Driven by the same plasma power supply, the lean ignition boundary of RMPI and CSI were tested and compared. If bright and stable flame was observed three times in the same working condition, and the ignition was considered successful. When the oil–gas ratio is lower than this oil–gas ratio, it cannot be successfully ignited, so this oil–gas ratio is recorded as the ignition oil–gas ratio of lean oil under corresponding working conditions. Figure 14 shows the ignition boundary of the three igniters with poor oil.

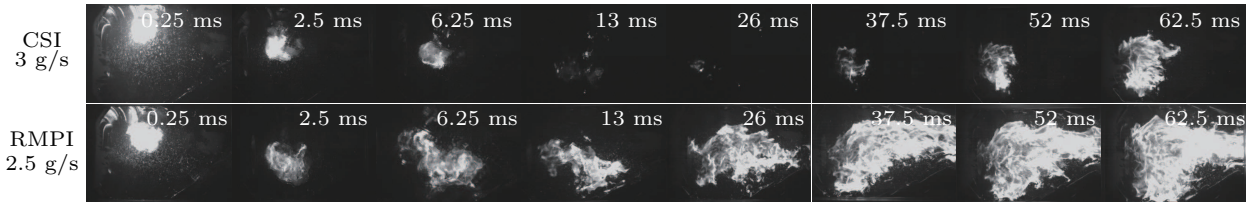


Fig. 13. Ignition process of CSI and recessed five-channel plasma igniter under ground condition.

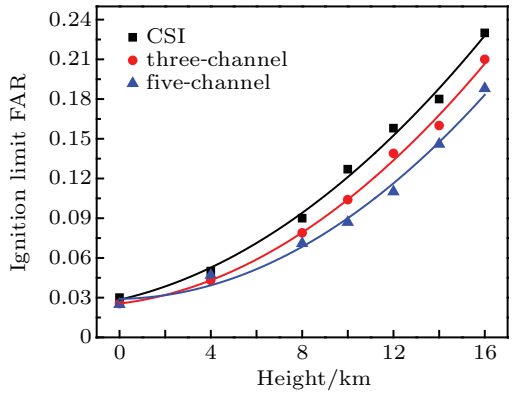


Fig. 14. Lean ignition boundaries at different heights.

As can be seen from Fig. 14, the ignition oil–gas ratio of lean oil increases with the increase of height. This is because as the height increases, the air becomes thinner, the incoming flow density decreases, and the inlet flow rate of the combustion chamber decreases, resulting in the poor atomization quality of the fuel in the combustion chamber, and the poor mixing effect of the combustible oil and gas mixture, which is not conducive to ignition. Air pressure is another major parameter, and as the height increases, the pressure in the combustion chamber decreases. In a low-pressure environment, the critical fire kernel radius of the oil and gas mixture becomes larger, and more energy is needed to form the initial fire kernel. However, the discharge energy of the igniter decreases under low-pressure conditions, and the energy injected into the fire kernel also decreases. Therefore, the ignition oil–gas ratio of lean oil increases with the increasing of height. By comparing the oil–gas ratio of lean oil ignition of three igniters under the same working condition from the fitting curve, it can be found that there is little difference in the oil–gas ratio of the three igniters in the ground state. At high altitude, compared with CSI, the RMPI show obvious advantages. Both RMPI configurations have the best widening effect at the height of 10 km. The percentage of lean ignition boundary widening of the three-channel plasma igniter can reach 18%, while that of the five-channel plasma igniter can reach 31%. The five-channel igniter has a smaller oil/gas ratio, a larger percentage of oil/gas boundary widening, and better ignition performance. The experimental results show that the RMPI is superior in ignition performance under real conditions.

4. Conclusion

In this paper, a multichannel plasma igniter with a circular cavity is proposed, and two configurations of three-channel and five-channel are designed. Based on the test method of igniter's spark energy of aviation gas turbine engine, the energy characteristics of three igniters are compared, and the ignition performance of three igniters is studied in real combustion chamber environment. The main conclusions are as follows.

(i) In a discharge period, the discharge energy of the RMPI is significantly higher than that of the CSI, and the energy of the five-channel igniter is greater than that of the three-channel igniter. The discharge electric energy and thermal energy of CSI are only 5.2 J and 1.3 J respectively, while the five-channel plasma igniter with cavity can reach 8.6 J and 6.2 J, respectively. The conversion efficiency of electric energy is increased from 26% to 43%, and the conversion efficiency of thermal energy is increased from 25% to 73%, indicating that the RMPI has greater energy and higher energy conversion efficiency, which is conducive to the improvement of ignition ability.

(ii) With the increasing of height, the spark penetration depth and excitation area gradually increase, and the applied incoming flow helps increase the spark penetration depth. Within a certain height range, the penetration depth of the RMPI is greater than that of the CSI, and the excitation area is also larger, which can effectively increase the contact area with the combustible oil and gas mixture, which is expected

to increase the ignition probability and improve the secondary ignition ability under extreme conditions at high altitude.

(iii) Compared with the CSI, the RMPI has shorter ignition delay time and faster flame development, which can effectively broaden the lean ignition boundary. The experimental results show that the widening effect are best when the height is 10 km. A three-channel plasma igniter can widen the lean ignition boundary by 18%, while a five-channel igniter can broaden the ignition boundary by 31%. Therefore, the RMPI is more capable of achieving fast and reliable ignition.

The RMPI can generate more discharge energy and has better ignition ability, and five channels are better than three channels. In the subsequent experiments, it is necessary to further explore the influence of parameters such as cavity depth, cavity shape, and electrode spacing on the characteristics of the igniter, so as to seek the optimal igniter structure.

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