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Experimental investigation on electrical characteristics and ignition performance of multichannel plasma igniter*

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Relighting of jet engines at high altitudes is very difficult because of the high velocity, low pressure, and low temperature of the inlet airflow. Successful ignition needs sufficient ignition energy to generate a spark kernel to induce a so-called critical flame initiation radius. However, at high altitudes with high-speed inlet airflow, the critical flame initiation radius becomes larger; therefore, traditional ignition technologies such as a semiconductor igniter (SI) become infeasible for use in high-altitude relighting of jet engines. In this study, to generate a large spark kernel to achieve successful ignition with high-speed inlet airflow, a new type of multichannel plasma igniter (MCPI) is proposed. Experiments on the electrical characteristics of the MCPI and SI were conducted under normal and sub-atmospheric pressures ($P = 10$–100 kPa). Ignition experiments for the MCPI and SI with a kerosene/air mixture in a triple-swirler combustor under different velocities of inlet airflow (60–110 m/s), with a temperature of 473 K at standard atmospheric pressure, were investigated. Results show that the MCPI generates much more arc discharge energy than the SI under a constant pressure; for example, the MCPI generated 6.93% and 16.05% more arc discharge energy than that of the SI at 30 kPa and 50 kPa, respectively. Compared to the SI, the MCPI generates a larger area and height of plasma heating zone, and induces a much larger initial spark kernel. Furthermore, the lean ignition limit of the MCPI and SI decreases with an increase in the velocity of the inlet airflow, and the maximum velocity of inlet airflow where the SI and MCPI can achieve successful and reliable ignition is 88.7 m/s and 102.2 m/s, respectively. Therefore, the MCPI has the advantage of achieving successful ignition with high-speed inlet airflow and extends the average ignition speed boundary of the kerosene/air mixture by 15.2%.

Keywords: multichannel plasma igniter, high-speed inlet airflow, ignition energy, ignition performance

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1. Introduction

Reliable high-altitude relight is of great importance for the performance and safety of jet engines.[1,2] The low pressure, low temperature, and high-speed inlet airflow at high altitudes (especially above 8 km) make high-altitude relight extremely difficult[3] and result in a decrease in the saturation vapor pressure of kerosene,[4] leading to poor kerosene evaporation and a slow chemical reaction.[5]

The instant the spark kernel forms, the flow field near the spark kernel is critical for successful ignition.[6] For instance, high-speed inlet airflow will cause incomplete spark kernel development and partial quenching may appear,[7,8] which results in unsuccessful ignition. Successful ignition depends on the ignition energy deposited into the combustible mixture forming an initial spark kernel of critical size in a short time, and the spark kernel will eventually decay and cannot reach the so-called critical flame initiation radius if the energy is insufficient.[9] The critical flame initiation radius, which depends on the Lewis number of the deficient reactant, is proportional to the flame thickness.[10] Therefore, at high altitudes with low pressure and high-speed inlet airflow, the flame thickness and the critical flame initiation radius become larger. To achieve successful ignition, a larger spark kernel needs to be generated with high-speed inlet airflow.

Non-equilibrium plasma, the fourth state of matter,[11] is a promising technology for ignition and combustion control[12,13] because of its unique ability to produce active species, heat, and modifying transport processes.[14] Wolk[15] studied the important role that critical spark kernel size played on ignition in a constant volume combustor. Several discharge methods can increase the initial spark kernel size. Yu[16] used a multi-coil power supply to generate distributed spark discharge that produced a faster and earlier flame kernel growth than that of the single high-energy spark. Briggs[17] compared several ignition methods including multi-electrode ignition and showed that a large effective flame kernel and/or a long kernel lifetime is very important for ignition in lean conditions. Nakamura[18] found that multi-point spark ignition can reduce ignition delay time, increase the combustion efficiency, and extend the lean ignition limit. Hnatiuc[19] proposed a double-spark ignition system with a higher ignition energy and larger plasma discharge area than conventional igniters. Sliding arc discharge, which has the ability to in-

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crease spark kernel size, has been widely used in recent years. Matveev[20] developed a new type of plasma igniter based on sliding arc discharge that demonstrated a reliable high-altitude relight performance. Leonov[21,22] found that the ignition of sliding arc discharge has the capacity of igniting a large area, and the ignition delay time of n-heptane was shortened by 500 μs. However, many practical difficulties exist in these works; for instance, complicated and bulky power supplies were adopted, extra gas sources were required, and the structures of the so-called new types of igniters were too complex for installation.

In this study, a new type of multichannel plasma igniter (MCPI) using a common ignition power supply is proposed to generate a large spark kernel and to achieve successful ignition with high-speed inlet airflow. The objective of this study is to assess the performance of two ignition methods, the semiconductor igniter (SI) and the MCPI, and to demonstrate the advantages of the MCPI in high-speed inlet airflow. Ignition experiments of kerosene under different velocities of inlet airflow at 473 K and standard atmospheric pressure were conducted in a triple-swirl combustor. The ignition energy, size of plasma heating zone, lean ignition fuel–air ratio (FAR), and maximum velocity of inlet airflow that can achieve successful ignition by SI and MCPI were measured and compared.

2. Experimental setup

2.1. Semiconductor igniter and multichannel plasma igniter

As shown in Figs. 1 and 2, two types of igniters were adopted in this experiment—the SI and the self-designed six-electrode MCPI. The SI consisted of a central and an outer grounded electrode separated by a ceramic insulator with a gap width of 1 mm that ended in a thin layer of silicon carbide. The semiconducting layer promotes ionization between the two electrodes and generates sparks at comparatively lower voltages. The ionization path formed by the ionized plasma originally shows a fine filament, and a powerful arc discharge occurs after an ionization path is created between the two electrodes.

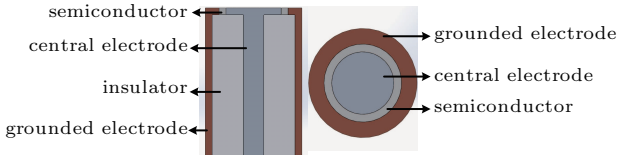


Fig. 1. (color online) Conventional semiconductor igniter.

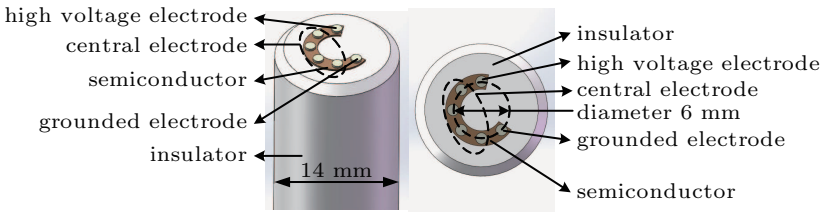


Fig. 2. (color online) Multichannel plasma igniter setup.

A multichannel discharge technique based on the concept of voltage relays put forward by Zhang[23] was adopted in designing the MCPI. The MCPI was composed of six nickel-copper alloy electrodes, a semiconductor, and a ceramic insulator made of 95% alumina ceramic. As shown in Fig. 2, six 1.2-mm-diameter cylindrical electrodes were arranged on a 6-mm diameter circle with a C-type layout. The gap width was 1 mm and the height of electrodes above the surface of the ceramic insulator was 0.5 mm. In addition, a 0.1-mm layer of silicon carbide was coated near and among the electrodes.

2.2. Plasma ignition power supply and discharge system

A schematic of the plasma ignition power supply and discharge system is presented in Fig. 3. A high-energy ignition power supply with stored energy of 12 J, a maximum peak-to-peak voltage of 8 kV, and a maximum frequency of 10 Hz was adopted. To quantify the ignition energy, the applied voltage and discharge current were measured by a 75-MHz high-voltage probe (Tektronix P6015A) and a 120-MHz current probe (Pearson 6600), respectively, and the two signals were recorded by a digital oscilloscope (Tektronix DPO4104).

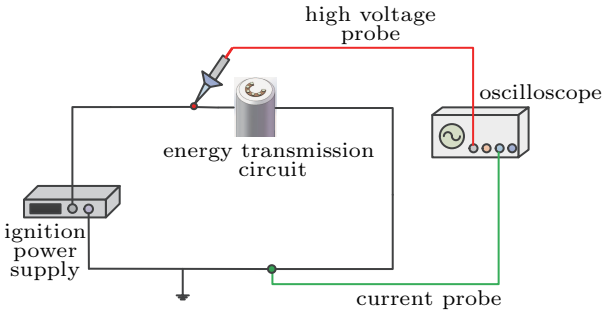


Fig. 3. (color online) Plasma ignition power supply and discharge system.

2.3. Simplified igniter discharge energy testing system

Successful ignition requires the injection of sufficient energy into a combustible mixture; the minimum of such energy is called the minimum ignition energy.[24] To characterize discharge energy by igniters more intuitively and to find how it changes with the number of channels, a simplified igniter discharge energy testing system with a pressure-tight cavity was adopted. By measuring the temperature of air inside the pressure-tight cavity, the heating effect on the surrounding air by arc discharge can be measured. As shown in Fig. 4, the system mainly consisted of two parts: the upper part was a stainless steel cylindrical sleeve. On the top surface of the sleeve a M6×12 threaded hole was arranged for a type-K thermocouple (WRN-02 with a measuring range of 0–800 °C) to insert and measure the temperature of air inside the cavity. The temperature was displayed on an AK6-DKL temperature controller. On the other side, a M14×1.25 internal thread was fitted with the ceramic external thread, and the lower part was the MCPI with an outer thread of M14×1.25 that formed a pressure-tight cylindrical cavity together with a cylindrical sleeve. The probe of the type-K thermocouple was flush with the top surface of the cylindrical cavity, and the entire system was fixed vertically between two parallel support plates.

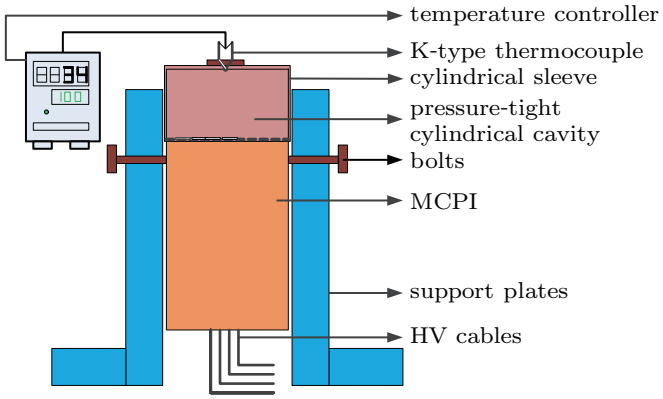


Fig. 4. (color online) Simplified discharge energy testing system of MCPI.

2.4. Triple-axial swirler combustor and combustion testing system

The ignition experiment was conducted in the triple-axial swirler combustor[25] of Nanjing University of Aeronautics and Astronautics and consisted of a diffuser, a liner, an SI, and MCPI igniter, casing, and a dome. The dome comprised a fuel nozzle and a fixed triple swirler. To simulate the particle size distribution of fuel atomization in a real aircraft engine, a single-channel centrifugal nozzle instead of a dual nozzle was employed in the experiments. The liner was made of high temperature alloy, and the diffuser was joined with casing with a quartz window on one side of the combustor to visualize the primary zone combustion status.

As shown in Fig. 5, the entire combustion testing system was mainly composed of a gas source, an electric heater, a triple-swirler combustor, an ignition system, a test system, and a piping system. The air in the test system was provided by a single-screw air compressor heated up to 523 K by an electric heater. The fuel supply system mainly included a fuel pump, valve, and nozzle, and RP-3 aviation kerosene was chosen. The ignition system consisted primarily of an ignition power supply, multichannel plasma igniter, semiconductor igniter, and cables. The test system included a thermocouple, orifice meter, fuel pressure gauge, and data acquisition system. The temperature of the inlet airflow was tested by a single nickel chrome/silicon thermocouple with measuring points at the center of the cross section with a measuring range of 273–1373 K and permissible error of 0.4% (T-273) (T represents the measured K temperature). The mass flow rate of the air was measured by an orifice meter with a permissible error of 1%. The fuel nozzle was calibrated in advance and was measured by a high-precision pressure gauge (YB-150 with a range of 10 MPa and precision grade of 0.25) installed before the nozzle.

As shown in Fig. 5(b), the bright self-sustaining stable flame observed through the window demonstrates successful ignition.

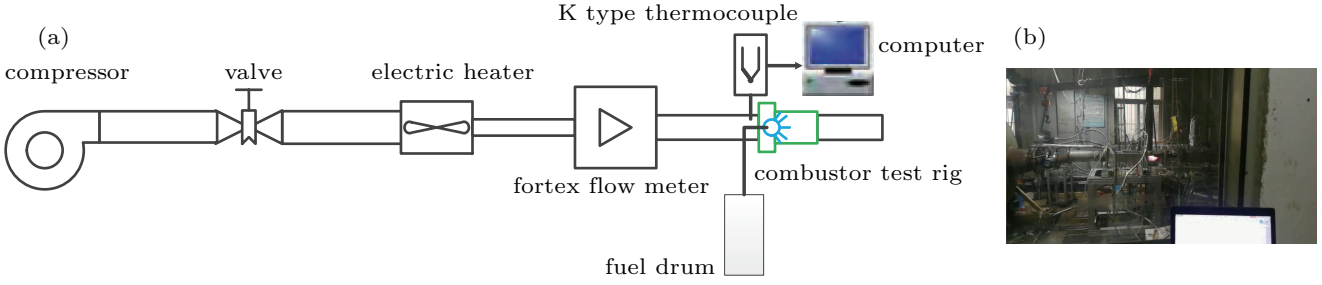


Fig. 5. (color online) (a) Triple-swirler combustor and combustion testing system and (b) successful ignition.

3. Results and discussion

3.1. Electrical characteristics

3.1.1. Electrical characteristics of several-igniter discharge

Five identical semiconductor igniters were adopted. Only one ignition power supply was used to drive one, two, three, four, or five igniters simultaneously and is called the "several-igniter discharge" mode. The discharge energy was calculated in two ways: one method obtained the first peak of the absolute power value to calculate the total discharge energy of several igniters, which is called power peak (PP) energy. The other method obtained a discharge period (DP) to calculate the total discharge energy, which is called DP energy as shown in Fig. 6. The PP and DP energies were both calculated as

$$E = \int_0^{\mathrm{t}} V(t)I(t)\,\mathrm{d}t, \tag{1}$$

where $V(t)$, $I(t)$, and E denote the applied voltage, instantaneous current, and ignition energy per pulse, respectively. The PP and DP energies were calculated when t denotes the first peak of the absolute power value or a discharge period, respectively.

The calculated PP and DP energies shown in Fig. 6(c) are represented by a red line and blue line, respectively. The figure shows that the PP energy was lower than that of the DP energy with the same power and number of igniters applied because the PP discharge time was less than that of the DP. With an increase in number of applied igniters, the total discharge energy of the several-igniter discharge increases gradually, but the increase rate of energy declines. This can be explained by using the following formula:

$$Q_{\mathrm{dis}} = \frac{nR_{\mathrm{d}}}{nR_{\mathrm{d}} + R_0} Q, \tag{2}$$

where Q, Q_{dis}, R_0, and R_{d} denote the ignition power supply stored energy, the discharge energy, the cable resistance, and the resistance of a single igniter, respectively. The discharge energy approaches that of the stored energy of the ignition power supply with an increase in the number of igniters applied; therefore, the calculated PP and DP energies are not always in line with the number of igniters applied. At first, R_{d} is smaller than R_0 when the number of igniters is less than four, and the calculated PP and DP energy are almost in line with the number of igniters applied. However, R_{d} becomes larger than R_0 with an increasing number of igniters applied; therefore, the discharge energy of the several-igniter discharge increases gradually, but the rate of energy declines. The total discharge energy of an igniter consists of two parts: the arc discharge energy and the energy dissipated by cables. Since the load resistance increases with an increase in arc and cable length, the consumed energy increases.

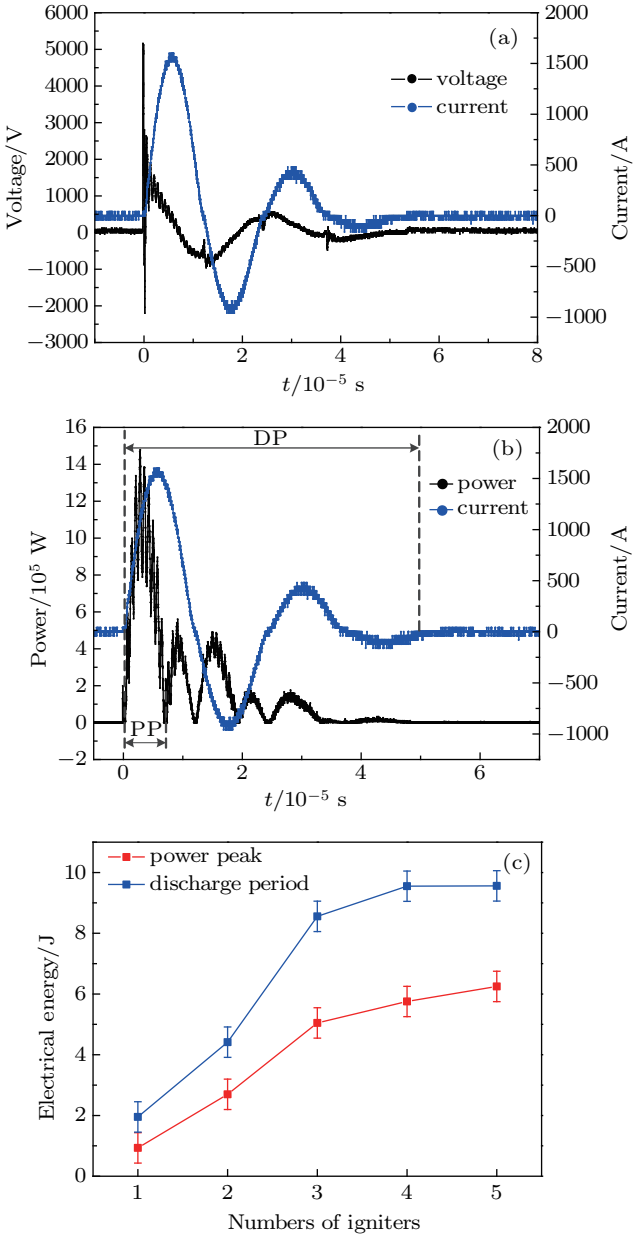


Fig. 6. (color online) (a) Voltage–current waveforms of several-igniter discharge, (b) two methods of calculating electrical discharge energy, and (c) calculated PP and DP energy.

To eliminate the effects caused by the increasing length of cables, the simultaneous discharge of one, two, three, four, or five igniters can be achieved. The arc discharge energy of the last igniter, which has no cable energy loss, was measured during the discharge process of the several-igniter discharge. Since the semiconductor igniters are identical, and if the cable loss energy has been eliminated, the total arc discharge energy is approximately equal to the product of arc discharge energy of the last igniter and the number of igniters applied as shown in Fig. 7(b).

As shown in Fig. 7(b), as the number of igniters applied increases, the total arc discharge energy increases gradually, but the rate of increase declines. The results show that the energy efficiency of the ignition power supply increases with an increase in the number of igniters. Five-igniter discharge

achieved 199% more DP energy than a conventional semiconductor igniter, increasing the energy efficiency from 17.42% to 52.08%. For PP energy, the five-igniter discharge attained 225% more energy than a conventional semiconductor igniter, increasing the energy efficiency from 10.67% to 34.72%, approximately 2.25 times higher. Therefore, in subsequent experiments, the PP energy calculating method was adopted because the vast majority of energy was released during the discharge time of PP energy. In this experiment, the number of igniters was gradually increased, and when six igniters were applied, discharge did not occur. The main reason for the discharge failure is that the breakdown process is more difficult with an increase in the number of igniters. Arc discharge cannot occur because the breakdown condition cannot be satisfied.

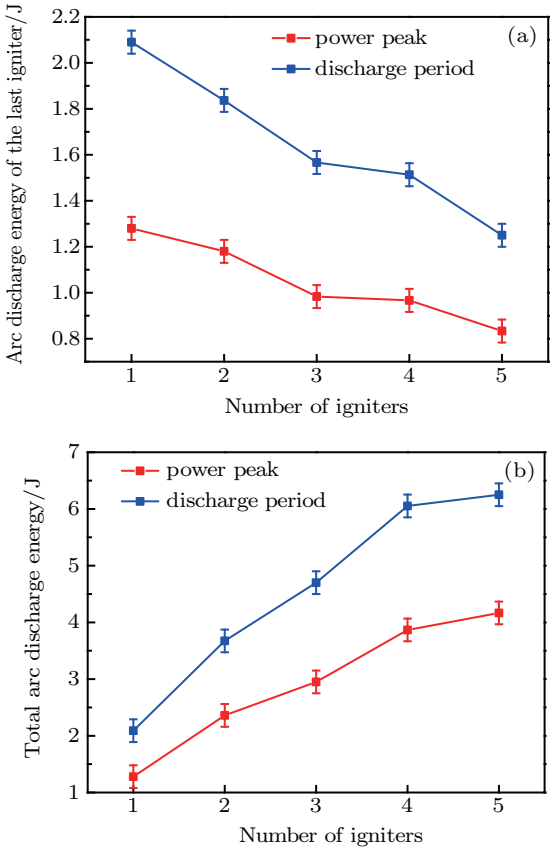


Fig. 7. (color online) (a) Arc discharge energy of last igniter of several-igniter discharge and (b) total arc discharge energy of several-igniter discharge.

3.1.2. Thermal and electrical characteristics of multi-channel plasma igniter

From the viewpoint of discharge energy, when driven by one power supply, the several-igniter discharge was superior to the one-igniter discharge, so a new type of self-designed MCPI with the advantages of several-igniter discharge was adopted. Experiments on the thermal characteristics of MCPI were conducted at 305 K. The heating effect to the surrounding air by arc discharge was measured, and figure 9 shows the temperature of the air inside the pressure-tight cavity as a function of time.

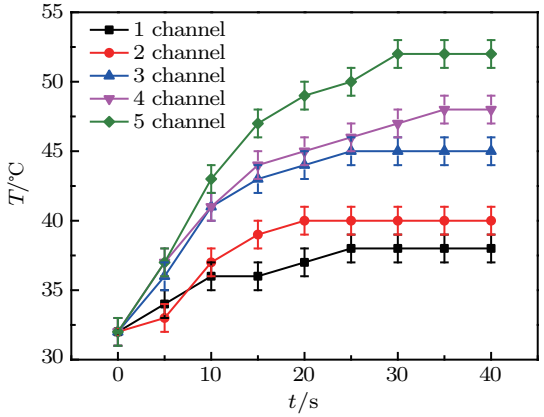


Fig. 8. (color online) Change of temperature inside pressure-tight cavity with time.

According to Fig. 8, the air temperature inside the pressure-tight cavity gradually increased after the discharge started and then reached thermal equilibrium after 35 s. As the number of discharge channels increased, the air temperature inside the airtight cavity rose faster, and the temperature at which the air eventually reached thermal equilibrium was much higher. Therefore, the multichannel discharge enabled the arc discharge to release much more heat at a higher speed and attain a greater heating effect on the air around the arc, making it easier to heat the combustible mixture and achieve successful ignition.

The discharge energy of the MCPI was quantitatively measured and the results are shown in Fig. 9. It can be seen that as the number of channels increased, the total arc discharge energy of the igniter increased gradually, especially when the pressure was above 30 kPa.

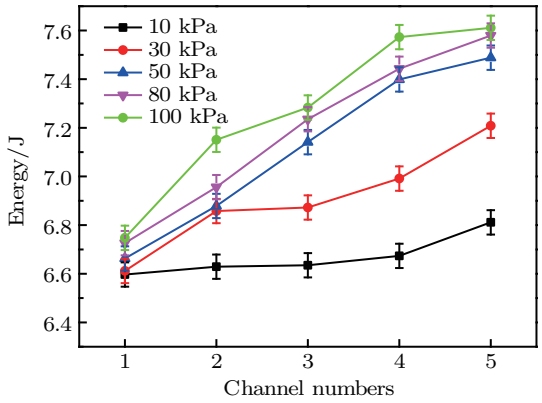


Fig. 9. (color online) Arc discharge energy of MCPI under normal and sub-atmospheric pressures.

The energy percentage improvement of the self-designed MCPI compared with conventional semiconductor igniters is shown in Fig. 10. When the pressure increased from 10 kPa

to 50 kPa, the percentage of energy sharply improved from 3.25% to 12.11%. When the pressure increased from 50 kPa to atmospheric pressure, the percentage of energy increased slowly from 12.11% to 13.81%.

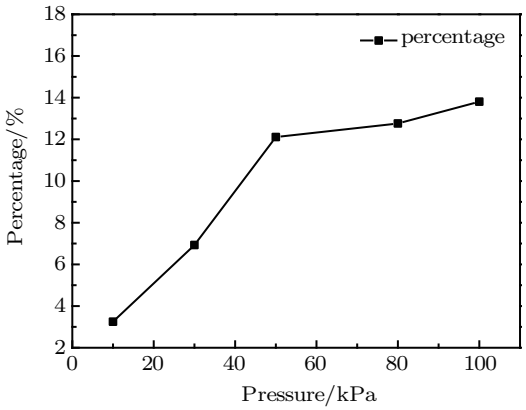


Fig. 10. Percentage of measured arc discharge energy of MCPI greater than SI.

The discharge images of the one- to five-channel plasma igniters under different pressures are shown in Fig. 11. It can be seen that under a certain pressure, with an increase in the number of channels, the length of the arc increased. The arc of the five-channel plasma igniter was nearly five times longer in length than that of the single-channel plasma igniter, and the discharge area was also larger.

The size and height of the plasma heating zone were measured under atmospheric pressure. A high-speed CCD camera was used for imaging the plasma heating zone and the discharge area of the igniters. The camera resolution was 256×128 pixels with a frame rate of 380000 and an exposure time of 0.82 μs. Figure 12(a) shows the heating zone development of the MCPI and SI connected in series to ensure simultaneous discharge of the MCPI and SI. Compared to a conventional SI, a larger plasma heating area (from top view) and a higher height of plasma heating zone (from side view) was achieved by the MCPI as shown in Fig. 12(b). Therefore, the MCPI generated a larger plasma volume and quickly growing heating zone. Since the MCPI is able to attain a higher arc discharge energy and create a much larger plasma volume and heating zone than that of the SI, it achieves successful ignition more easily in fuel lean kerosene/air mixtures with a high-speed inlet airflow.

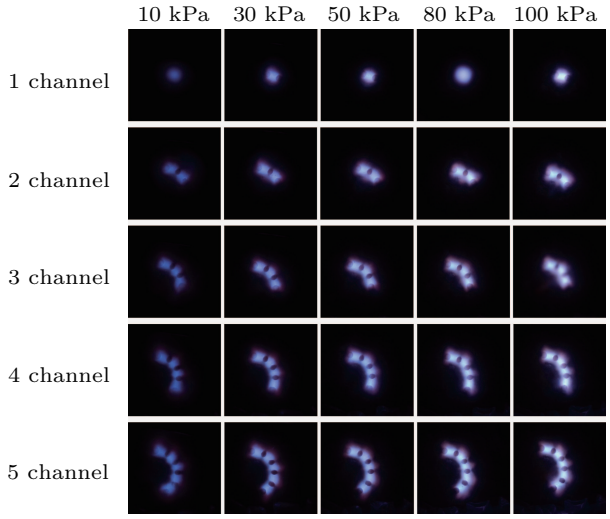


Fig. 11. (color online) Discharge images of different channels under normal and sub-atmospheric pressures.

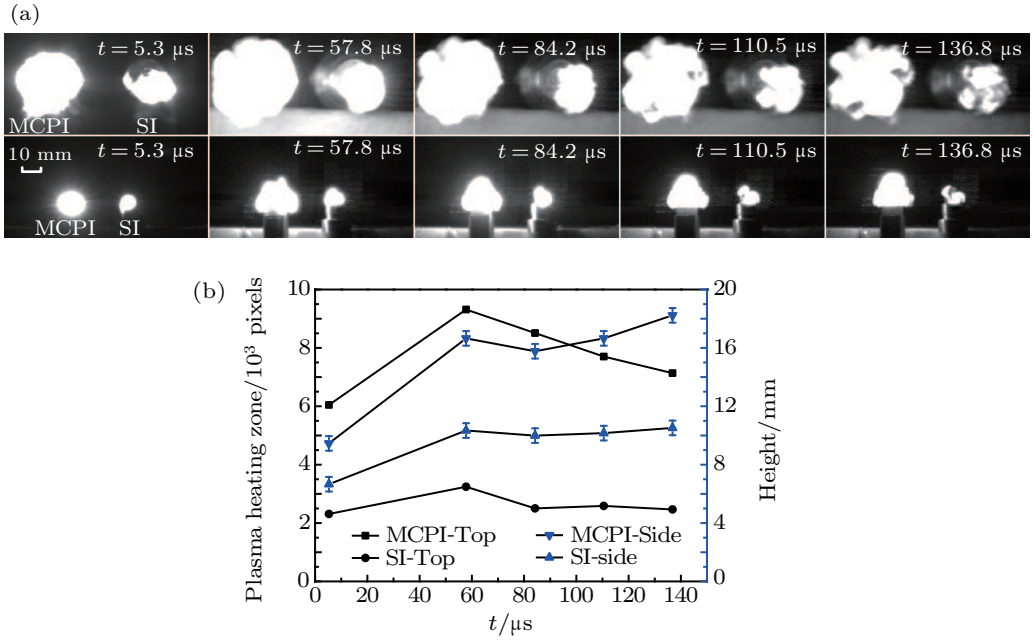


Fig. 12. (color online) (a) Heating zone development and (b) heating zone size and height of plasma heating zone of MCPI and SI in air (MCPI-Top and MCPI-Side means from the top view and side view of MCPI, and SI-Top and SI-Side means from the top view and side view of SI, respectively).

3.2. Ignition performance

3.2.1. Experimental setup of ignition tests

Many factors including pressure, temperature, fuel–air ratio (FAR), inlet airflow velocity, spark kernel size, and spark energy influence ignition performance. The combustor's overall FAR varied from 0.022 to 0.032. The present experiments were conducted at atmospheric pressure with an inlet airflow temperature of 473 K to study the effects of two types of igniters and with different inlet airflow velocities (60–110 m/s) to study the ignition performance of a triple-swirler combustor.

Under a certain inlet airflow velocity, the ignition power supply was first turned on, then the electromagnetic valve of the fuel pump was opened, and the mass flow rate of kerosene was gradually increased. If a bright, self-sustaining, stable flame was observed through the window installed in the test section, successful ignition was assumed, and the mass flow rate of both the airflow and kerosene were recorded to obtain an overall combustor FAR under this working condition; otherwise, ignition was assumed to be unsuccessful.

Ignition tests were conducted at least three times after successful ignition at a certain mass flow rate of inlet airflow to ensure it was a lean ignition FAR and it was not possible to achieve successful ignition below that FAR. The mass flow rate of the inlet airflow was changed to validate the relations between the lean ignition FAR and velocity. Ignition tests were carried out under different FARs and Fig. 13 shows the lean ignition FAR as a function of velocity. A conventional SI and the self-designed MCPI were adopted in the ignition tests.

3.2.2. Results and analysis of ignition test

It can be seen from Fig. 13 that the lean ignition FAR decreased with an increase in the velocity of the inlet airflow. Generally, the increasing velocity of inlet airflow produced two effects. One effect is that the increasing inlet airflow increased the flow rate at the nozzle to maintain the FAR, and the pressure drop of the nozzle increased correspondingly and increased the injection speed of the kerosene mist out of the nozzle. Meanwhile, the increased turbulence intensity enhanced the interaction between the kerosene and air and improved the atomization performance of kerosene, which is favorable for ignition. The other effect is that despite the slightly increased arc discharge energy of the igniter, a high-velocity inlet airflow is not conducive to successful ignition. Here, the first effect plays the major role.

As shown in Fig. 13, the maximum velocity of inlet airflow where the SI achieved successful ignition was approximately 88.7 m/s, and ignition was unsuccessful when the velocity was greater than 88.7 m/s. The maximum velocity of inlet airflow where the MCPI achieved successful ignition was approximately 102.2 m/s. The MCPI achieved successful ignition and maintained stable combustion at a higher inlet airflow velocity because it has a higher ignition energy, larger initial discharge area, larger plasma heating area, and higher penetration depth, thus achieving the goal of successfully extending the ignition speed boundary by 15.2%.

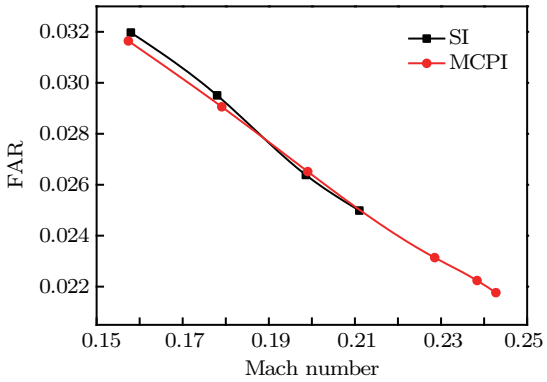


Fig. 13. (color online) Ignition speed boundary at high temperature and ambient pressure.

The arc discharge energy released by a conventional SI is far less than the 12-J stored energy of the ignition power supply and is difficult to enhance. The development of plasma technology has surpassed multichannel discharge technology, and a new type of MCPI the same size as an SI has been proposed to generate a higher arc discharge energy and larger plasma volume than the conventional SI to significantly increase the initial spark kernel size and ignition probability of the MCPI. Moreover, the MCPI and SI are both driven by the same original ignition power supply.

4. Conclusions

A multichannel plasma igniter was proposed to increase the arc discharge energy and the plasma heating zone to induce a larger spark kernel and achieve successful ignition under a high-speed inlet airflow. Ignition experiments for kerosene/air mixtures in a triple-swirler combustor under different velocities of inlet airflow were conducted. The ignition performances of a conventional SI and the MCPI were compared, and the advantages of the MCPI for ignition of a triple-swirler combustor under a high-speed inlet airflow were demonstrated. The main conclusions are as follows.

The total arc discharge energy of the several-igniter discharge and the energy efficiency of the ignition power supply increases with an increase in the number of igniters. A five-igniter discharge can attain a 199% higher discharge period energy than that of a one-igniter discharge and increase the energy efficiency from 17.42% to 52.08%. A five-igniter discharge can achieve 225% more power peak energy than a one-igniter discharge and increase the energy efficiency from 10.67% to 34.72%, which is approximately 2.25 times higher.

The upper limit of the number of applied igniters in this experiment was five.

Under a certain pressure, the total arc discharge energy of the self-designed MCPI increases with an increase in the number of channels, especially when the pressure is above 30 kPa. Compared to a conventional SI, the energy improvement of the self-designed MCPI is obvious; for example, when the pressure increased from 10 kPa to 50 kPa, the improved-energy percentage changed from 3.25% to 12.11%.

The minimum-ignition FAR decreases with an increase in the velocity of the inlet airflow, and because the increased turbulence intensity enhances the interaction between kerosene and air, the atomization performance of kerosene improves, which is favorable for ignition. The new type of MCPI the same size as a conventional SI can generate a higher arc discharge energy and greater plasma volume than a conventional SI and significantly increase the initial spark kernel size and ignition probability of the MCPI. The maximum velocity of inlet airflow where the MCPI can achieve successful ignition is approximately 102.2 m/s, while that of a conventional SI is approximately 88.7 m/s. The ignition probabilities of the SI drop quickly with an increase in inlet airflow velocity while the MCPI has much higher ignition probabilities. Above all, the MCPI achieved the goal of successfully extending the ignition speed boundary by 15.2% and is of vital importance to the design of aircraft engines.

Further research should aim at the enhancement of ignition performance of the MCPI at low pressure and low temperature and extend the speed and FAR ignition boundaries.

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