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XJTU: Typical Arrangements for Downstream Uniformity Assessment in Atmospheric-Pressure Plasma Jet Arrays

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ABSTRACT The downstream uniformity of the atmospheric-pressure plasma jet array is a key technical problem in regards to large-scale applications. This paper presents a 2-D array device of five jets arranged in four different shapes designed from the perspective of symmetry. Various schemes were tested to determine the effects of jet arrangement on the downstream uniformity of the array: the completely symmetrical array X, the completely asymmetrical array J, and semi-symmetrical arrays T and U. The interactions in the arrays were observed via optical imaging as well as electrical and spectroscopic characterizations. The results show that the downstream plume pattern markedly changes with the jet arrangement. Peripheral plumes suppress the internal plumes to varying extent under different jet arrangements. The emission intensity of the helium line at 706.5 nm was taken as a criterion to find that downstream uniformity under the arrangements J, T, U, and X gradually decreases as the jet arrangement grows increasingly symmetrical. The electric field simulation shows that different jet arrangements cause various degrees of inhomogeneous electric field distributions, which in turn affect the charge transferred into each plasma jet and the distributions of active particles resulting in downstream uniformity variations. The results presented here may provide a theoretical foundation for improving the downstream uniformity of the plasma jet arrays and achieving large-scale plasma jet sources.

INDEX TERMS Plasma jet, cold plasma, array, uniformity, jet arrangement.

I. INTRODUCTION

The atmospheric-pressure plasma jet has been a popular research subject over the past two decades owing to significant advantages such as low temperature, generation of abundant reactive species, simple treatment operation, and low cost [1]–[7]. It is a favorable approach to surface treatment, especially for certain temperature-sensitive materials (e.g., biological materials, composite insulation materials) and complex-shaped workpieces [8]–[12]. However, the action area of most atmospheric-pressure plasma jets is usually less than 1 cm², which greatly limits their practical applications [13]. To remedy this, researchers have proposed plasma jet arrays consisting of several closely spaced jets covering larger-scale treatment areas.

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The plumes out of the tubes are usually inconsistent due to the complex interactions between jets in a given array [14], [15]. Many researchers have investigated the mechanisms of these jet-jet interactions in various attempts to improve the downstream uniformity of the arrays. For example, Babaev and Kushner [16] revealed that the interactions in the array mainly include electrostatic repulsion, hydrodynamic interactions, and photo-ionization. Kim *et al.* [17] found that divergence of the edge plumes in a 1-D array are caused by electrostatic repulsion between the plasma bullets.

In recent years, efforts to improve the downstream uniformity of jet arrays have mainly centered on optimizing voltage source electrical parameters and the gas medium flow rate, adding current-limiting devices, and addition of small amounts of electronegative gas. Cao *et al.* [18] reported that voltage frequency significantly affects the

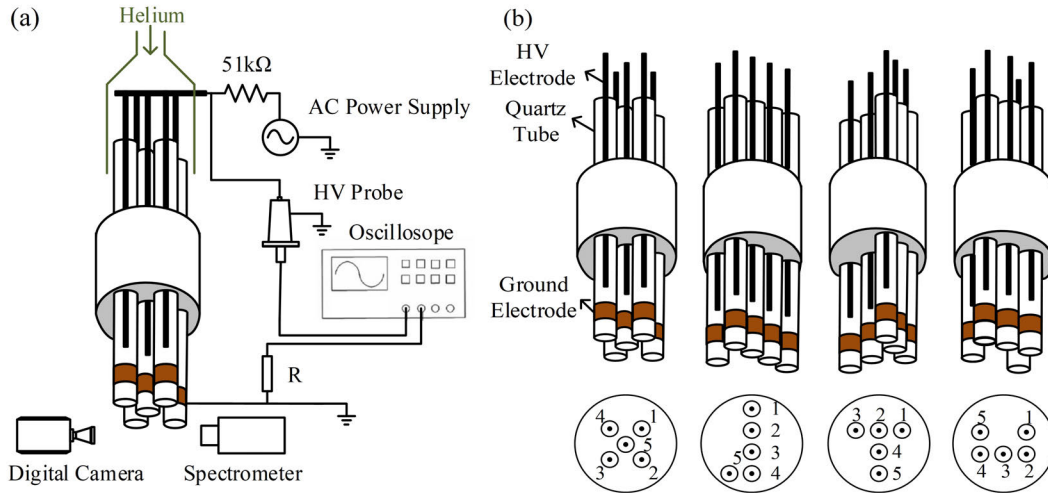


FIGURE 1. (a) Experimental setup (b) Plasma jet array schemes.

downstream uniformity of 2-D arrays; Hu *et al.* [19] designed a 2-D jet array with three jets driven by a radio-frequency pulse and direct-current pulse voltage to generate parallel plumes beams and divergent plume beams, respectively. Fan *et al.* [20] found that the conduction current of a single-electrode configuration array decreases as gas flow rate increases, which drives down the repulsion between jets. Ghasemi *et al.* [21] advised the addition of a resistor or capacitor in the circuit for this purpose. Zhang *et al.* [22] improved downstream uniformity by mixing oxygen into the gas flow.

One of the main advantages of the plasma jet array is that it allows for various action area shapes; the jet arrangement can be adjusted to suit various objects. Previous researchers have indicated that the jet arrangement could have a critical impact on the downstream uniformity of the plasma jet array [18], but there is yet a lack of systematic research on this issue. Inspired by the acronym of our university, we designed a series of five-plasma-jet schemes with equidistant arrangements: a completely symmetrical arrangement X, a completely asymmetrical arrangement J, and semi-symmetrical arrangements T and U. We explored the influence of these four arrangements on the downstream uniformity of the arrays from the perspective of symmetry. The results presented below may provide a theoretical foundation for achieving large-scale plasma treatment sources with variable action areas.

II. EXPERIMENTAL SETUP

A schematic diagram of the experimental setup used in this study is shown in Fig. 1(a), and the structural details of the four arrays (both side and vertical views) are shown in Fig. 1(b). Jets numbered from one to five were successively arranged in X, J, T, and U shapes. Each jet had the same needle-ring electrode structure. The spacing between jets was set to 1 mm to make the interactions more evident. A Teflon holder with five holes was used to keep the quartz tubes

parallel. The quartz tube of each jet was 180 mm in length and the inner and outer diameters were 3 and 4 mm, respectively. A tungsten needle with a diameter of 1 mm was fixed in the center of the quartz tube and connected to a high-frequency AC power source with the excitation frequency held at 10 kHz via a current limiting resistor as the HV electrode. A copper sheet with a width of 10 mm and a thickness of 0.5 mm was wrapped around the quartz tube at a position 10 mm away from the nozzle as the ground electrode. The distance between the tip of the HV electrode and the ground electrode was fixed at 10 mm. The gas supply (99.999% helium in purity) was divided into five identical branches through a gas diffusion device to feed the array at a flow rate of 5-10 L/min.

The voltage and current waveforms were measured by a 1000: 1 HV probe (Tektronix P6015A) and a 50Ω non-inductance resistor R in series in the circuit, respectively. The signals were recorded with a digital oscilloscope (Tektronix DPO-4104B). Images of the jet arrays were taken on a digital camera (Canon EOS 600D) with exposure time of 1s. The camera angles (side views) of these images were the same as the viewing angles of the side views shown in Fig. 1(b). The emission spectrums were captured by a spectrometer (Andor SR-500i) with an optical resolution of 0.05 nm and a measurement range of 200-1100 nm.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. PLUME CHARACTERISTICS

The downstream uniformity of the plasma jet array is mainly influenced by the electrical parameters of the power supply and the flow rate of the working gas [23], [24]. Images of four jet arrays at various peak-to-peak voltages V_{pp} are shown in Fig. 2. The jet numbers corresponding to the plumes are marked below the images. In order to accurately investigate the downstream uniformity under various jet arrangements, the variations of the plume lengths are shown in Fig. 3. The gas flow rate was set to 10 L/min throughout these

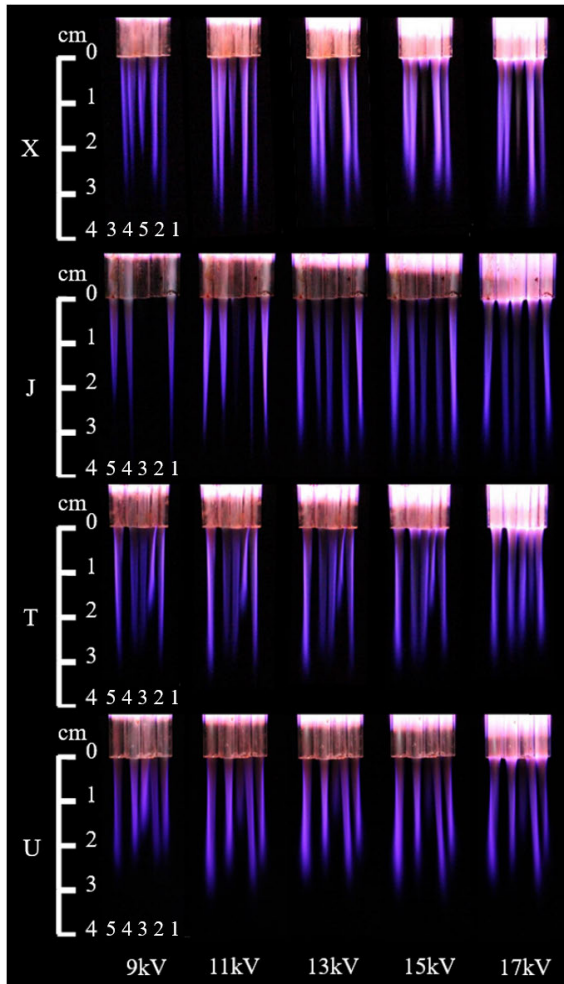


FIGURE 2. Images of jet arrays under various jet arrangements.

experiments. As shown in Fig. 2, when the applied V_{pp} reached 11 kV, the plumes of all five plasma jets in four arrays extended into the atmosphere. The lengths of the peripheral plumes were relatively consistent at this time. As the applied V_{pp} increased from 9 kV to 17 kV, the deflection angles of the peripheral plumes gradually increased due to the increased density of the charged particles, which enhanced the electrostatic repulsion between the plumes [20], [24].

The arrangement of jets has a significant impact on the plume characteristics of the array. As shown in Fig. 2 and Fig. 3, when the jets were arranged in the completely symmetrical X shape, the lengths of the side plumes tended to be consistent and evidently longer than that of the central plume. As the applied V_{pp} increased, the lengths of the side plumes increased at first and then slightly decreased. This may be due to the transition from laminar to turbulent flow at elevated gas temperatures [25], [26]. Although the central plume was subject to balanced electrostatic repulsion from the side jets without departing from its original orbit, it grew increasingly suppressed.

When the jets were arranged in the completely asymmetrical J shape, the peripheral plumes #1 and #5 showed

the strongest light intensity in the array. As the applied V_{pp} increased, their light intensities and lengths were fairly consistent (similar to the case of the 1-D array). As the applied V_{pp} increased from 11 kV to 15 kV, the lengths of the three plumes located in the middle positions were suppressed in order. After the applied V_{pp} reached 15 kV, the lengths of all five plumes tended to be consistent; the downstream uniformity of the array with this jet arrangement was preferable to the other three schemes.

When the jets were arranged in the semi-symmetrical T and U shapes, the lengths of the plumes in symmetrical positions were consistent while those located in relatively internal positions (such as jet #2 in array T and jet #3 in array U) were evidently suppressed by the adjacent plumes. As shown in Fig. 3, when the jets were arranged in the U shape, the plume lengths had an evident stratification phenomenon.

Three regular patterns were observed in the plume characteristics of the plasma arrays with above four jet arrangements at different voltages. First, the characteristics of the plumes in symmetrical positions were found to be generally the same. Second, the light intensities and lengths of the peripheral plumes were relatively stronger and longer. The peripheral plumes appeared to have suppressed the internal plumes, resulting in stronger suppression of the plumes closer to the center of the array. Third, the interactions between the plumes grew more intense as the applied voltage increased.

Fig. 4 shows images of four jet arrays taken at different gas flow rates with an applied V_{pp} of 12 kV. In order to make the location of each plume more evident, the jet numbers are marked below the images. It can be seen from Fig. 4(a) and Fig. 4(b) that as the gas flow rate increased, the downstream plume patterns of the arrays slightly changed; this suggests that the form of the interface between the working gas and the air fluctuated variously during the increase in gas flow rate under various jet arrangements [12], [27]. Additionally, as shown in Fig. 4(a)-(d), the deflection angles of the plumes subjected to unbalanced electrostatic repulsion decreased as the gas flow rate increased, which indicates that the gas flow rate is another key factor affecting plume divergence. It can be seen from Fig. 4(e) and Fig. 4(f) that the downstream area of the jet arrays appeared evidently inhomogeneous due to the repulsion between plumes. Therefore, it is preferable for the plasma jet array to scan the material when performing surface treatment. It is worth noting that the downstream plume patterns were unstable at the gas flow rate of 5 L/min. It gradually stabilized as the gas flow rate increased, thus, the array needs a sufficient gas flow rate to maintain stability.

The above results indicate that the jet arrangement is a key factor affecting the plume patterns of the downstream area. However, as shown in Fig. 2, there was an inconsistency in light intensity as well as length between the plumes. It is impossible to accurately evaluate the downstream uniformity simply based on such images, which will be further discussed in Section 3.2 through spectral methods.

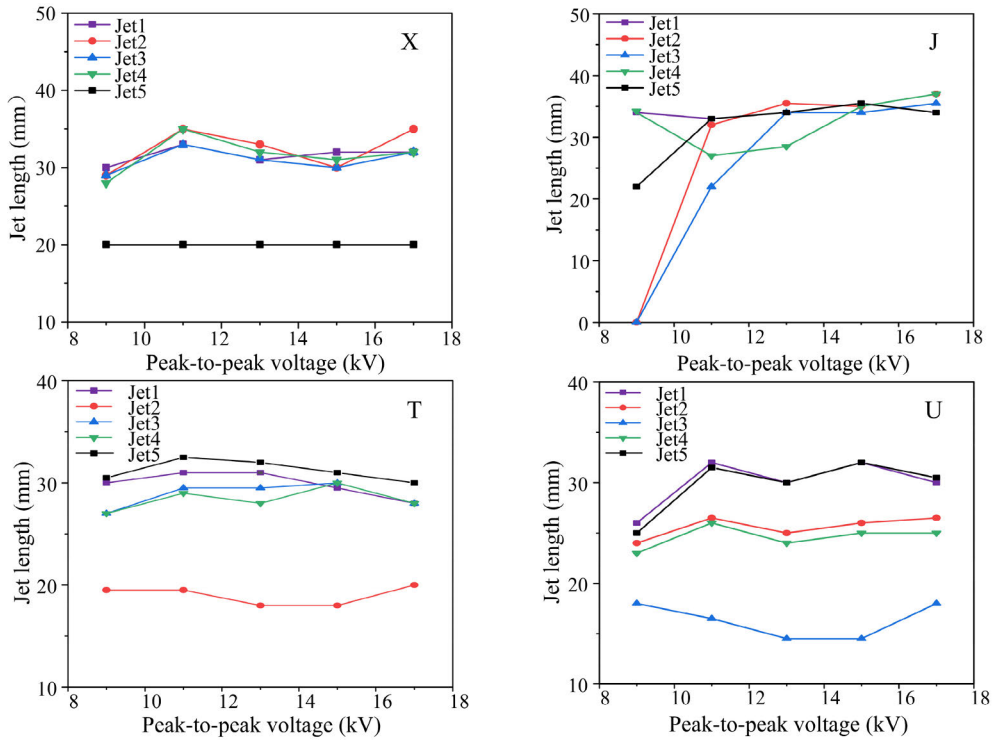


FIGURE 3. Plume lengths in jet arrays under various jet arrangements.

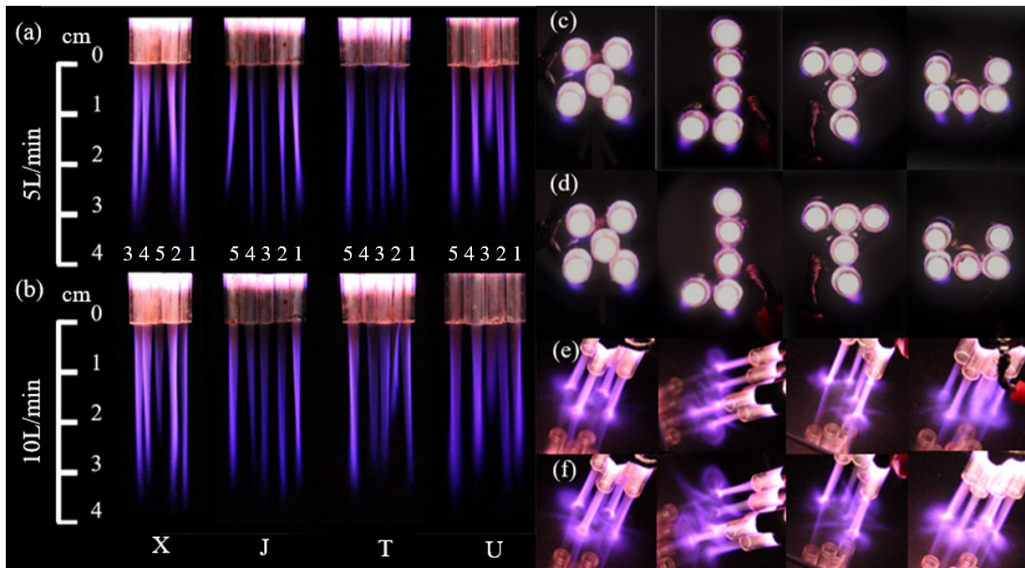


FIGURE 4. Images of jet arrays under various jet arrangements with gas flow rates of.

B. OPTICAL CHARACTERISTICS

We next measured the emission spectra of four arrays with the applied V_{pp} and gas flow rate set to 12 kV and 10 L/min, respectively to further investigate the effects of the jet arrangement on the optical characteristics, as shown in Fig. 5.

The emission spectra were transmitted through an optical fiber located at the side of the array in the position of 20 mm from the center and 10 mm from the nozzle.

As shown in Fig. 5, the spectral components under four jet arrangements were basically the same in this case. They were mainly dominated by the N_2 , N_2^+ and atomic He lines, while the OH and O lines appeared at 308.8nm and 777.4nm at the same time. By comparing four characteristic lines of OH at 308.8 nm, N_2 at 337.1 nm, He at 706.5 nm, and O at 777.4 nm, we found that the overall optical emission intensities of the arrays were closely consistent. This may indicate that the

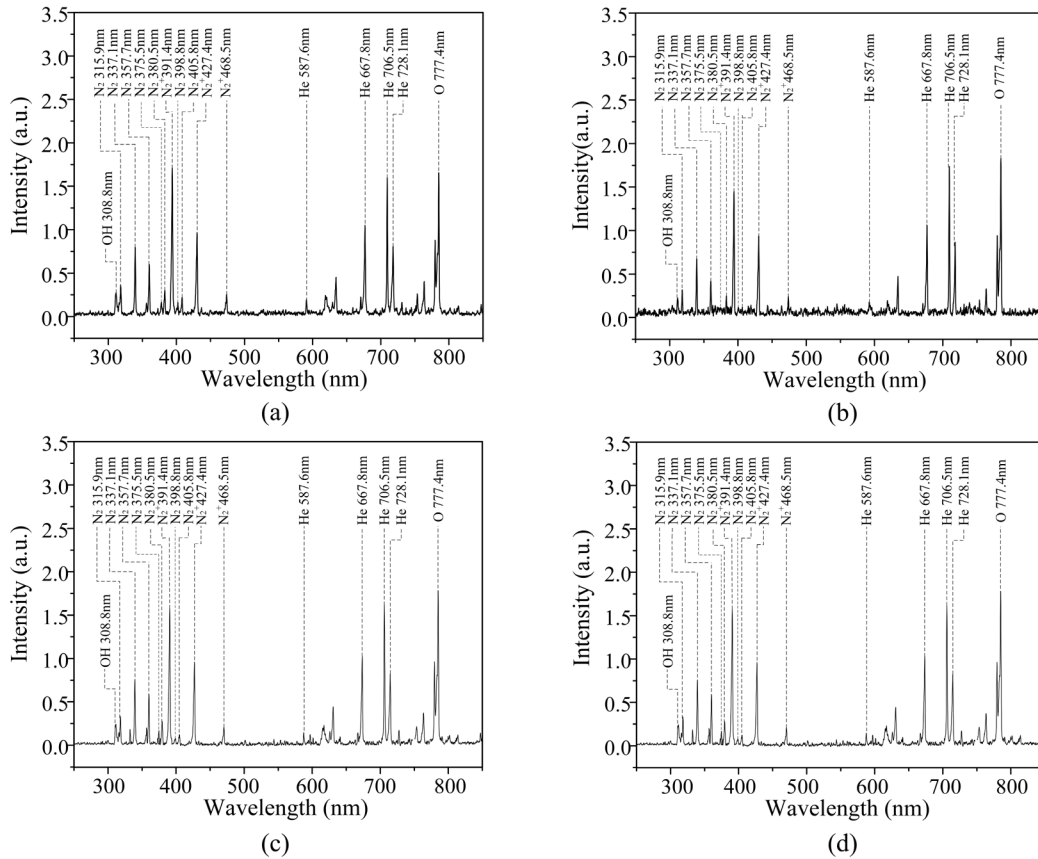


FIGURE 5. Emission spectra of jet arrays under various jet arrangements.

discharge intensity of the array does not change with the jet arrangement.

Previous studies have shown that the emission intensity at 706.5 nm indicates energetic electrons [28]. Supposing the electrons satisfy the Maxwell-Boltzmann distribution during the discharge process, the emission intensity of the jet at 706.5 nm may be a good indication of its discharge intensity. In order to accurately evaluate the downstream uniformity under four jet arrangement, we measured the emission intensity of each jet at 706.5 nm through a collimator located in the position of 10 mm from the plume and 5 mm from the nozzle, as shown in Fig. 6. The applied V_{pp} and gas flow rate in this case were 12 kV and 10 L/min, respectively.

As shown in Fig. 6, the emission intensities of the jets at 706.5 nm are further evidence of the phenomenon shown in Fig. 2. The emission intensities of the jets relatively located in the internal positions appeared to be weaker than those of the peripheral jets. The emission intensities of the jets in symmetrical positions showed close consistency. When the jets were arranged in X, J, T, and U shapes sequentially, the ranges of the emission intensities of five jets were 0.511, 0.323, 0.427, and 0.487, respectively. In effect, using the emission intensity at 706.5 nm as a standard of the jet-jet uniformity indicates that the downstream uniformity of the array under the completely asymmetrical arrangement J is

optimal, followed by the arrays under the semi-symmetrical arrangements T and U, and the array under the completely symmetrical arrangement X is the least desirable.

C. ELECTRICAL CHARACTERISTICS

In order to investigate the effects of the jet arrangement on the electrical characteristics, we measured the voltage-current waveforms of the arrays with the applied V_{pp} and gas flow rate set to 12 kV and 10 L/min, respectively, as shown in Fig. 7. The discharge currents under four jet arrangement were all sinusoidal and capacitive with maximum values of up to 20 mA, which indicates strong mutual coupling between the jets. The current waveforms of four jet arrays were basically the same at the same applied voltage, though a slight difference in the positive pulse peak value was observed.

The discharge power P and transferred charge Q of the array can be calculated as follows [29]:

$$P = \frac{1}{T} \int_t^{t+T} u(t)i(t)dt \tag{1}$$

$$Q = \int_t^{t+T} i(t)dt \tag{2}$$

where T is the current period, $u(t)$ and $i(t)$ are the instantaneous applied voltage and discharge current. As the applied

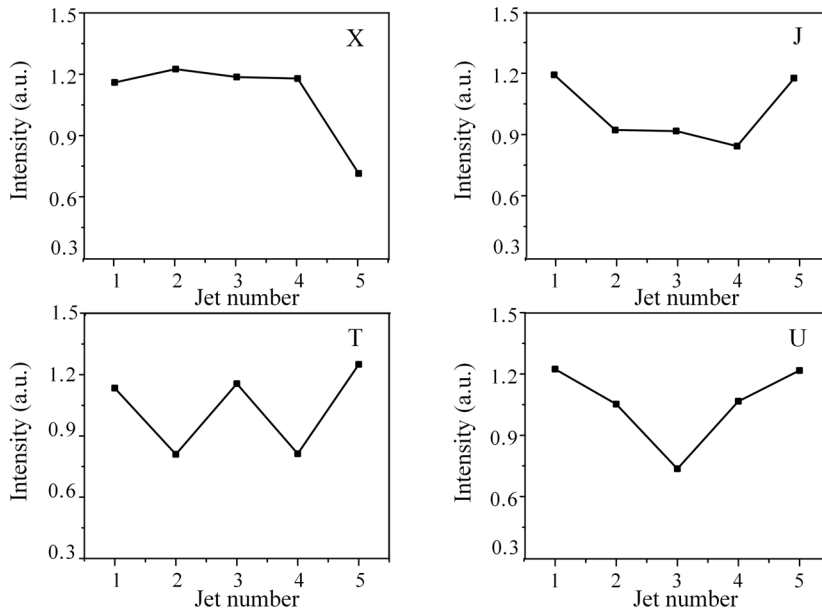


FIGURE 6. Emission intensities at 706.5 nm of individual jets under various jet arrangements.

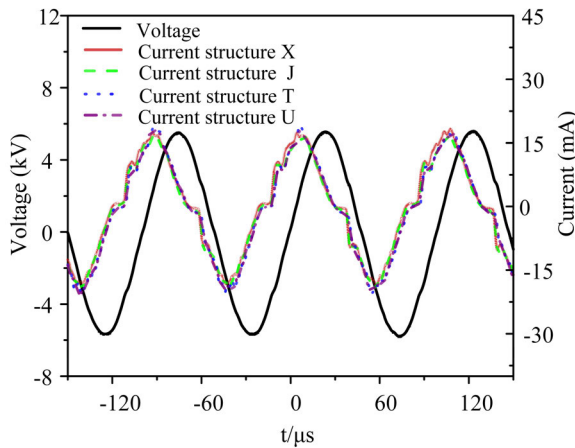


FIGURE 7. Voltage-current waveforms of jet arrays under four jet arrangements.

V_{pp} increased from 9 kV to 18 kV, P and Q increased monotonically from 8.3 W and 489 nC to 45.0 W and 1679 nC on average, respectively. We also found that the discharge energy and transferred charge were consistent under different jet arrangements, which supports the spectral observations presented in Section 3.2.

In addition, the discharge currents of the arrays remained stable as the gas flow rate increased from 5 L/min to 10 L/min. This observation departs from the conclusion of a previous study on a 2-D array with a single needle electrode structure [20], which indicates that the addition of the ground ring electrode may alter the pattern of the interactions in the plasma jet array. This phenomenon can be exploited to suppress the influence of the gas flow rate on the discharge characteristics and improve the stability of the array.

The results of our experiment suggest that the jet arrangement of the atmospheric-pressure plasma jet array has an impact on its downstream uniformity. The jet-jet uniformity improves as the arrangement varies from a honeycomb X-shaped array to a J-shaped array, which is similar to a 1-D array. Spectral results show that the jet arrangement affects the consistency of the emission intensities at 706.5 nm. The emission intensity at 706.5 nm has been proved to be markedly affected by the electric field intensity, from which we can speculate that the variation in downstream uniformity under various jet arrangements is related to the electric field distribution.

To further observe the influence of the electric field distribution on the downstream uniformity, we simulated the electric field distributions under four jet arrangements. The cross-sectional electric field distributions inside the quartz tubes and the electric field intensities at the tips of the HV electrodes with an applied voltage of 6 kV in COMSOL, as shown in Fig. 8 and Fig. 9.

We found that the electric field intensities reach their maximum values at the tips of the HV electrodes. As shown in Fig. 8 and Fig. 9, the electric field distributions are evidently inhomogeneous under four jet arrangements. The electric fields of the periphery jets are significantly stronger than those of the internal jets. As shown in Fig. 8, when a certain jet is adjacent to another jet, the electric field on the adjacent side is suppressed. The electric field of a certain jet is suppressed at a larger spatial angle when it is adjacent to more jets from different angles. Another pattern was observed in the simulation wherein adjacent jets close together show a greater impact on their respective electric field. We conclude that the electric field distribution of a certain jet is a result of the combined effect of the number of adjacent jets and

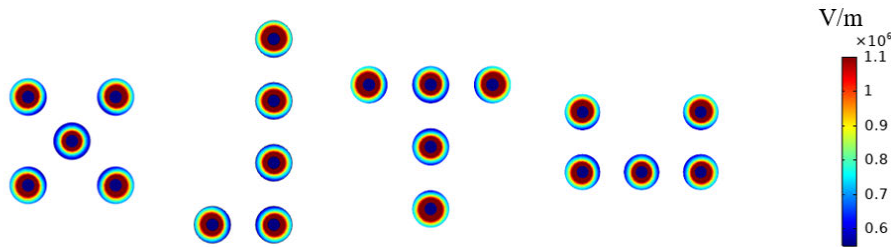


FIGURE 8. Cross-sectional electric field distributions at HV electrode tips under various jet arrangements.

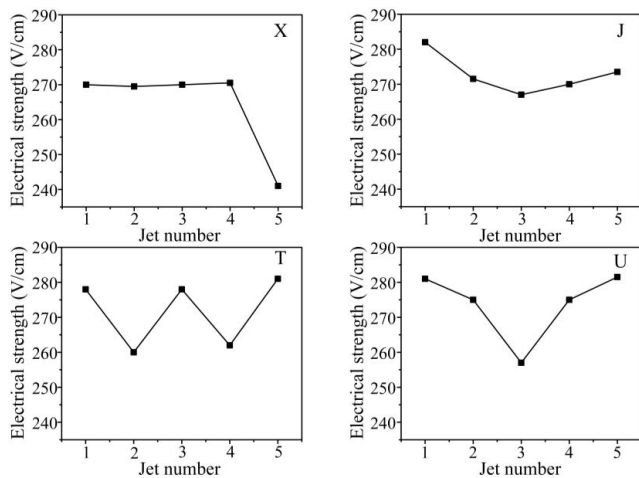


FIGURE 9. Electrical field strengths at HV electrode tips under various jet arrangements.

the distance from them. Consider the electric field of the X-shaped array as an example, the electric field of the middle jet #5 is suppressed by the four side jets at a short distance, resulting in severe inhomogeneous electric field distribution of the array.

As shown in Fig. 9, the electric field intensities of the jets at the tips of the HV electrodes show a similar pattern to the emission intensities at 706.5 nm. The ranges of the electrical strengths of five jets at HV electrode tips are 28.0, 15.0, 21.5, and 23.5 kV/cm respectively when the jets are arranged in X, J, T, and U shapes sequentially. The difference in electrical strength among the jets increases as the arrangements are in J, T, U, and X shapes sequentially. Combined with the result discussed in Section 3.2, we can obtain that the jet-jet uniformity is closely related to the electric field distribution of the array.

As mentioned above, the transferred charge in the circuit did not change significantly under different jet arrangements in our test, though the inhomogeneous electric field distributions would cause the transferred charge to be unevenly distributed to the jets to various degrees [30]. According to the plasma bullet model of the plume, the charge transferred into the bullet will increase under stronger electric fields resulting in a higher bullet propagation speed [2], [31]. An increase of the charge transferred into the plasma bullet

can also enhance the photoionization process and further increase the intensities of active particles remaining at the tail of the bullet. Certain active particles with longer durations (e.g., N_2) can truncate the appearance time of the plasma bullet resulting in earlier discharge in areas with higher electric field intensities [25]. Therefore, the downstream uniformity of the plasma jet array can be improved by optimizing the electric field distribution by means of improving the jet arrangement.

IV. CONCLUSION

In this paper, four 2-D atmospheric-pressure plasma jet arrays with the jets arranged in X, J, T, and U shapes were designed from the perspective of symmetry to investigate the influence of jet arrangement on the downstream uniformity of the array. The optical images showed that the jet arrangement has an impact on the downstream plume characteristics. The peripheral plumes appeared to suppress the internal plumes to varying degrees. The spectral results showed that the emission intensities of the jets at 706.5nm are influenced by the jet arrangement. Combined with the optical images, we found that the downstream uniformity gradually improves as the jet arrangement sequentially varies from the completely symmetrical array X to the semi-symmetrical arrays T and U, followed by the completely asymmetrical array J. The electrical results showed that the discharge energy and transferred charge in the circuit do not change significantly under various jet arrangements. We simulated the electric field distributions to find mutual suppression between the electric fields of the jets. The degree of inhomogeneous electrical field distribution varies with different jet arrangements, which affects the downstream uniformity of the array.

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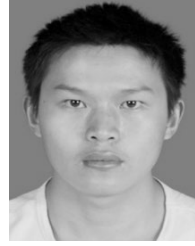
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