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Research Paper

Optical Diagnostics for Dual Jet Interactions of Helium Atmospheric Pressure Plasmas

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ABSTRACT

In this study, the interactions of dual plasma jets have been optically diagnosed for various alignment angles, gas flow rates, and applied voltage conditions to investigate the interactions of plasma plumes emitted from each jet. An anti-parallel alignment of the dual jets with in-phase voltage waveforms had a repulsive interaction. In contrast, the perpendicular alignment results in an attractive interaction when the applied voltage and gas flow rate are sufficiently large. We found that the mechanisms of the attractive and repulsive interactions are strongly related to the electrostatic potential distributions between the dual jets.

Keywords: Atmospheric pressure plasmas, Schlieren image, Dual plasma jets, Plasma plumes

1. Introduction

Unlike low-pressure plasma reactors, atmospheric pressure plasmas (APPs) can generate reactive chemical species without a vacuum vessel and pumping equipment [1]. In addition, because APPs are not in equilibrium, they retain ambient gas temperature. Thus, APPs are often used for surface treatment, processing of polymers, and biomedical applications [2–9]. The chemical interactions in APPs are being actively studied for the surface treatment of polymers [5].

Among many electrode configurations of APPs, plasma jets are a popular tool for generating plasma plumes from tubes with Ar or He gas flow [6, 9]. The breakdown voltage of plasma jets is much lower than that of air discharge, and their plasma bullets are faster [6] than sound for delivering charges and chemical species to distant target surfaces. In addition, the gas flow rate can be varied to change discharge characteristics. However, the treatment area of a single plasma jet is limited to less than one square centimeter, which limits applications in the uniform treatment of large-area surfaces. For this reason, there have been studies on using arrays or bundles of small plasma jets in parallel [10–12]. However, in this case, a strong repulsive force with each plasma plume is reported, resulting in diverse propagation trajectories. Furthermore, the laminar flow length is reduced, and surface treatment remains insufficient [10]. Deflection angles are larger in He jets than in Ar jets because He is lighter than Ar and the Ar jet array is more controllable and stable than the He jet array. A lower applied voltage and a higher gas flow rate are more effective for a uniform one-dimensional jet array [11]. In contrast, the plasma jet arrays produce an intense and enhanced plasma jet, especially when the target surface is a conductor or biased [12].

However, the interactions of multiple plasma jets for different interaction angles have not been studied in detail so far. As the plasma jet emits bullet-like charges like a bullet [6] in addition to gas flow mixed with radicals and excited states, the interaction of two plasma bullets propagating in opposite directions or to rectangular angles is a scientifically relevant phenomenon. This study investigated the interaction of two APP jets using helium gas with different voltage driving methods. Optical diagnostics were obtained with the Schlieren image method and an intensified charge-coupled device (ICCD).

The experimental setup and conditions are explained in Sec. 2, followed by the results for the variation of alignment, gas flow rate, and the applied voltage in Sec. 3. Finally, conclusions are presented in Sec. 4.

2. Experimental setup

Figure 1 shows the experimental setup used when measuring the Schlieren images of the interaction of two plasma jets; it consists of two plasma jets, a power supply, two parabolic mirrors, a knife-edge, and a mass flow controller (MFC). The driving frequency is fixed at 20 kHz for both the jets with the same phase. The diameter and focal length of the parabolic mirrors are 150 mm and 1.54 m, respectively. We used the same plasma jet used in Tang *et al.* [6] and Lee *et al.* [9]. The outer and inner diameters are 8 and 4 mm, respectively, and the distance from the grounded electrode covering the exterior dielectric to the high voltage electrode is 25 mm. The gas flow rate and applied voltage are the most critical variables in the experiment. The gas flow rate was varied from 1 to 2.5 standard liter per minute (SLM) at an

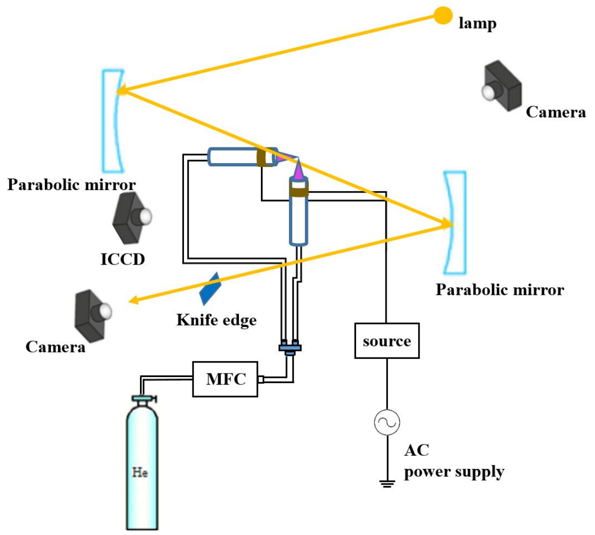

Figure 1. Experimental setup for the alignment of the two jets and Schlieren image measurement.

interval of 0.5 SLM. The applied sinusoidal voltage of 3 to 4 kV was selected with a driving frequency of 20 kHz.

Two alignments of anti-parallel and perpendicular directions were tested. When the two jets are aligned horizontally facing one another, as shown in Fig. 2(a), the distance between the two jets was set to 20 mm, and when the two jets are aligned perpendicularly, the distance between the two endpoint centers is 10 mm. The experiment was conducted by connecting one common power source to the two jets to ensure that the voltage phase of the two sources is the same. We also tested the out-of-phase case by applying two different power sources to the jets, as shown in Figs. 2(c) and 2(d). However, except for this case, we used in-phase voltage waveforms.

3. Results

Figure 2 shows the experimental setup of the two He plasma jets facing each other, called the anti-parallel alignment. The gas flow rate was fixed to 2 SLM, and the distance between the endpoints of the two jets was 20 mm. When the applied voltage was put in phase by connecting the same power source to the two devices, the two jets were repulsive, as shown in Figs. 2(b) and 2(d). However, the two jets attract each other when the applied voltage is out-of-phase by applying two different voltage sources to the two jets. The attraction is more effective when the distance between the two jets is shorter and when the applied voltage is larger.

Figure 3 shows the Schlieren images of the in-phase anti-parallel two-jet alignment. Figure 3(a) shows the case of 1.5 SLM at each side without an applied voltage, where the two He gas flows merge at the center and flow upward. Figure 3(b) is the case of 3 kV and 1.5 SLM, where the gas flows upward right after the nozzle ends, indicating that the horizontal momentum is reduced on both sides by the plasma bullets propagating in the opposite direction. When the gas flow rate increases to 2 SLM, as shown in Fig. 3(c), the right-hand side jet is momentarily weakened, and the gas flow is downward while the left-hand side jet is approximately straight. Figure 3(d) shows the case of 4 kV and 2.5 SLM where the repulsion is stronger. These repulsive properties are similar to those observed in the parallel one-dimensional jet array [10, 11].

In contrast, Fig. 4 shows the experimental setup of the two He plasma jets perpendicular to each other, called the perpendicular alignment. The inlet in Fig. 4 shows the photo obtained for the attractive and outward flow cases even when there are in-phase voltage waveforms on both sides. When the applied voltages are out-of-phase, the two jets bend inward to merge in the manner shown in Fig. 2(c). Fig-

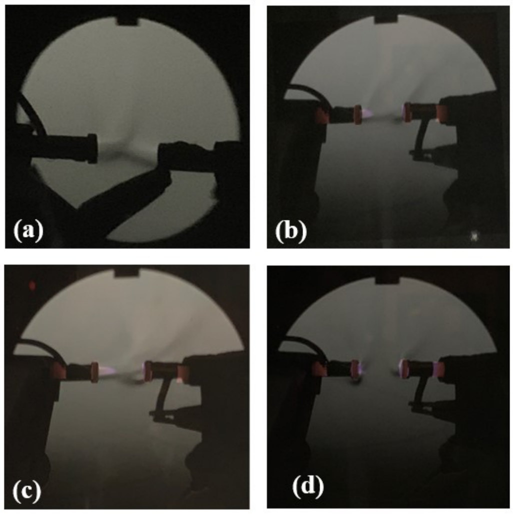

Figure 3. Schlieren images of the anti-parallel alignment for the gas flow rates and applied voltages of (a) 0 V, 1.5 SLM, (b) 3 kV, 1.5 SLM, (c) 3 kV, 2 SLM, and (d) 4 kV, 2 SLM.

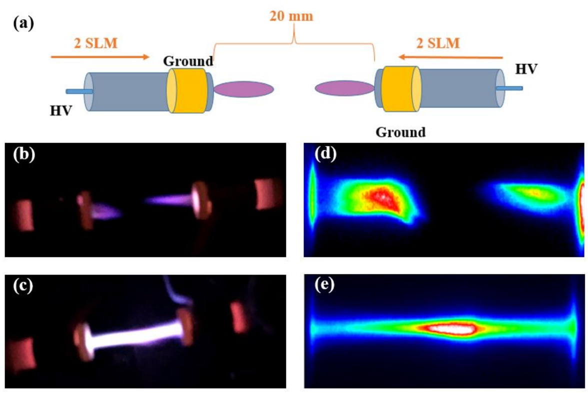

Figure 2. (a) the anti-parallel two-jet alignment resulting in (b) a repulsive interaction with in-phase or (c) an attractive interaction for out-of-phase voltage waveforms at the two jets. In addition, ICCD images with an exposure time of 10 ms are provided for (d) in-phase and (e) out-of-phase voltage waveforms.

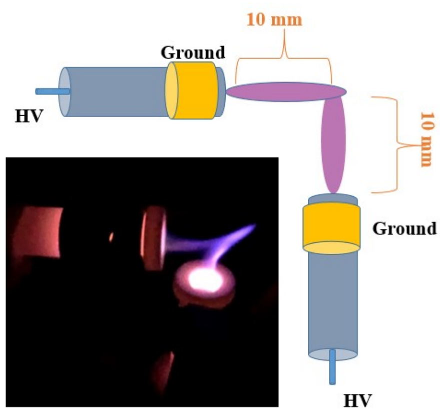

Figure 4. Perpendicular two-jet alignment and the photo image of the two-jet interaction (inlet), resulting in an outward attractive propagation with in-phase voltage waveforms at each jet.

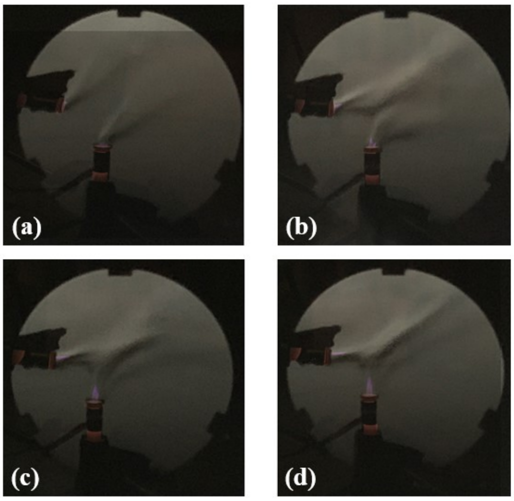

Figure 5. Schlieren images of the perpendicular alignment for the applied voltages and gas flow rates of (a) 3 kV, 1 SLM, (b) 3 kV, 1.5 SLM, (c) 4 kV, 2 SLM, and (d) 4 kV, 2.5 SLM.

ure 5 shows the Schlieren image of the perpendicular alignment for the variation of the gas flow rate and applied voltage. When the gas flow rate is 1 SLM with an applied voltage of 1 kV, as shown in Fig. 5(a), the two jets are weak, and the gas flow is repulsive rather than attractive. With a gas flow rate of 1.5 SLM, as shown in Fig. 5(b), the two jets do not merge. Even with a larger gas flow rate, they do not merge effectively at 3 kV. However, when the applied voltage is increased to 4 kV at the gas flow rates of 2 and 2.5 SLM, the two jets perfectly merge toward 45 degrees outward, as shown in Figs. 5(c) and 5(d). We also checked the time-resolved ICCD images for these cases and found that two plasma bullets propagate following the gas channel. Interestingly, the two plasma bullets are not repulsive for an applied voltage that is large enough to create a channel.

Figure 6 shows the calculated electric potential profiles calculated using COMSOL multi-physics software. For simplicity, the space charge effect of plasmas was not included in the calculation. The electron kinetics were local because the charge was sufficiently close to being neutral, and the collisional mean free path of the electrons and ions was short. Thus, the effect of space charge is not significant for time-averaged profiles. In Fig. 6(a), the equipotential lines are represented by the white lines, and directions of the electric fields are perpendicular to the lines. The potential was normalized to its maximum voltage at the inner rods. As shown in Fig. 6(a), the outward attraction is possible for two jets with in-phase voltage waveforms because in this case, the equipotential lines open a wide range of electric field lines. On the contrary, the asymmetry disappears in the anti-parallel alignment.

However, when the applied voltages are 180-degrees out of phase for two jets close to each other, as shown in Fig. 6(b), a channel of electric fields makes the plasma bullets propagate from the positive side of the potential profile to the other side of another jet in an arc shape. Therefore, outward attraction occurs only when the voltage waveforms are in-phase for the two jets.

4. Conclusion

We tested the dual jet interaction with the variation of the alignment angles of two atmospheric pressure He plasma jets. We found that the repulsion and attraction of the two jets are sensitive to the potential profiles of the whole space. When the two jets are aligned in parallel, as reported previously [10–12], the repulsive force far from the center is dominant when the applied voltage is large, and the one-dimensional array becomes nonuniform. When the two jets are anti-

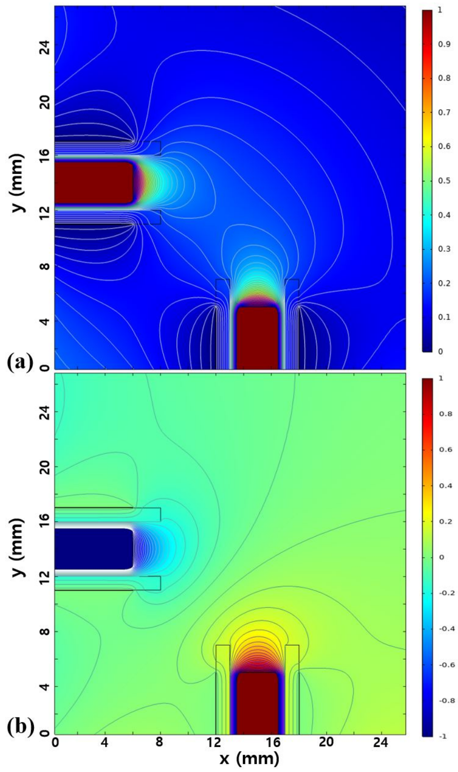

Figure 6. Spatial distribution of the electric potential (color) and equipotential lines calculated using the COMSOL multi-physics software for the perpendicular two-jet alignments with (a) an in-phase and (b) out-of-phase voltage waveforms at each jet. The potential is normalized to its maximum voltage in the inner rods.

parallel, the front ends of the two jets are repulsive when the voltage waveforms are in-phase. For both the parallel and anti-parallel alignments, the repulsion is enhanced with an increase in the applied voltage. In contrast, the perpendicular alignment induces an outward attraction of the two jets and is enhanced by increasing the applied voltage and gas flow rate.

The attraction and repulsion of the two plasma jets in the alignments of 0, 90, and 180 degrees does not follow an obvious pattern, but the basic mechanism of the interactions is related to the potential profiles. The plasma bullets are emitted only when there is positive potential in the inner electrode, and the electric field lines create an efficient guide for the plasma plume. Therefore, two- or three-dimensional plasma jets arrays along with the flexibility of the pointing angles rather than a one-dimensional array with a uniform parallel alignment are preferable for large-area treatment.

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Conflicts of Interest

The authors declare no conflicts of interest.

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