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The "plasma bullet" behavior of atmospheric pressure plasma plumes has recently attracted significant interest. In this paper, a specially designed plasma jet device is used to study this phenomenon. It is found that a helium primary plasma can propagate through the wall of a dielectric tube and keep propagating inside the dielectric tube (secondary plasma). High-speed photographs show that the primary plasma disappears before the secondary plasma starts to propagate. Both plumes propagate at a hypersonic speed. Detailed studies on the dynamics of the plasma plumes show that the local electric field induced by the charges on the surface of the dielectric tube plays an important role in the ignition of the secondary plasma. This indicates that the propagation of the plasma plumes may be attributed to the local electric field induced by the charges in the bulletlike plasma volume. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3079503]

I. INTRODUCTION

Because of enhanced plasma chemistry, atmospheric pressure nonequilibrium plasmas have been widely studied for several emerging applications such as surface and materials processings,[1,2] biological and chemical decontaminations,[3–6] absorption and reflection of electromagnetic radiation,[7,8] and synthesis of nanomaterials.[9] However, at atmospheric pressure, the breakdown voltages of working gases are very high. That is why the discharge gaps are usually in the range from a few millimeters to several centimeters, which substantially limit the size of materials to be treated for direct treatment.[3,10–13] In the process of remote treatment (indirect treatment), some short lifetime active species, such as oxygen atoms and charge particles, may have already disappeared before reaching the objects to be treated, which makes the efficiency of the treatment much lower.[14]

To address these issues, cold atmospheric pressure plasma jet (C-APPJ) devices have recently attracted significant attention.[15–24] Such plasma jet devices generate plasma plumes in open space (surrounding air) rather than in confined discharge gaps. Thus, they can be used for the direct treatment and there are no limitations on the sizes of the objects to be treated.

The fundamentals on the propagation of the atmospheric pressure plasma jets are not yet well understood. Teschke *et al.*,[25] Lu and co-workers,[26,27] Sands *et al.*,[28] Shi *et al.*,[29] and Ye and Zheng[30] studied the dynamics of the various plasma jets generated by different devices and sustained by different driving voltages. They all found that the plasma plumes are not a continuous volume of plasma; rather the plumes are more like a bullet formed by a small and well-confined plasma volume that travels from the exit aperture and terminates somewhere in the surrounding air. The speed of the "plasma bullets" varies from $\sim 10^4 - 10^5$ m/s, which is several orders of magnitude higher than the gas velocities. Further analysis shows that the C-APPJs are electrically driven, which is quite similar to positive streamer discharges. However, there are several significant differences between the bulletlike plasma plumes and the widely studied positive streamers (cathode-directed streamer).[31–33] For such positive streamers, the external electric field is in the range of several kV/cm. This is not the case for the plasma plumes. Since the plasma plume can be touched by a human hand without any harm,[20] the applied electric field along the plasma plume is most likely quite low. In addition, for a positive streamer, the streamer head is connected to the power electrode by a highly conducting channel, which acts as a metallic "needle" protruding from the power electrode (a perfectly conducting needle would be exactly at the anode potential): the field at the end of the streamer is greatly enhanced.[34] Obviously, this is not the case for the "plasma bullet," which looks like isolated from the power electrode. As can be seen from the high-speed photographs,[25,26,28,29] the track left by the plasma bullet is dark under most conditions. However, Lu *et al.*[27] recently suggested that the conductivity of the dark track left by the plasma bullet is low, but not negligible, which affects the propagation of the plasma bullet. Nevertheless, more studies are needed to have a better understanding of the plasma bullet behavior.

In this paper, a specially designed experiment is carried out to study the plasma bullet behavior. It is found that a helium primary plasma plume generated in the ambient air can propagate through the wall of a dielectric tube and continue propagating inside the tube (secondary plasma). Both plumes propagate at a hypersonic speed. This paper is organized as follows. The experimental setup is described in Sec. II. The details of the experimental results, including the dynamics of both plasma plumes, are presented in Sec. III. Finally, the discussion of the experimental results is given in Sec. IV and a brief summary of this work is presented in Sec. V.

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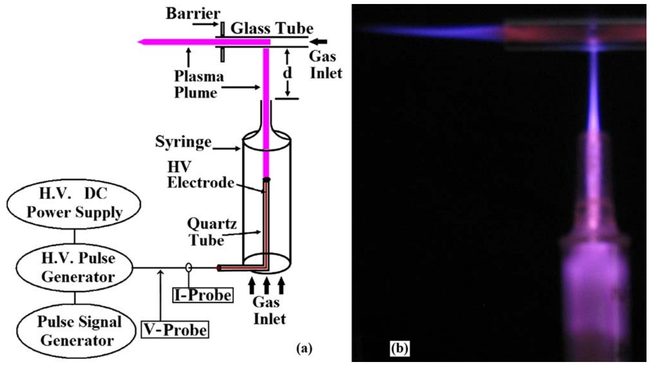

FIG. 1. (Color online) (a) Schematic of the experimental setup. The inner and outer diameters of the quartz tube are 2 and 4 mm, respectively. The inner diameter of the hollow barrel of the syringe is 6 mm and the diameter of the syringe nozzle is about 1.2 mm. The distance between the tip of the quartz tube and the nozzle is 1 cm. The distance d from the nozzle to the glass tube is 1.5 cm. The inner diameter of the glass tube is 2 mm. (b) Photograph of the plasma plumes with the applied voltage V_a of 9 kV, frequency of 4 kHz, pulse width of 800 ns, and helium flow rates of 2 and 3 l/min for the syringe and the glass tube, respectively.

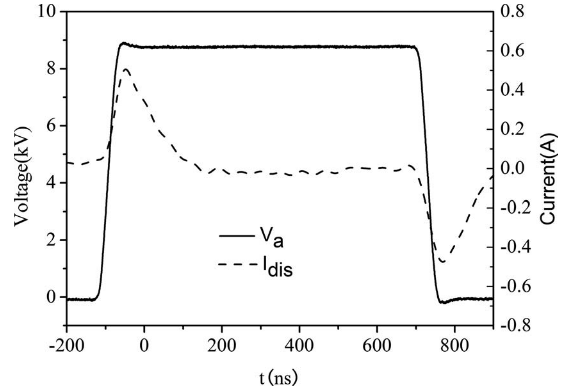

FIG. 2. The applied voltage V_a and actual discharge current I_{dis} vs time. The pulse frequency is 4 kHz.

II. EXPERIMENT SETUP

The schematic of the experiment setup is shown in Fig. 1(a). The high voltage (HV) wire electrode, which is made of a copper wire, is inserted into a quartz tube with one end closed. The quartz tube along with the HV electrode is inserted into a hollow barrel of a syringe. The distance between the tip of the HV electrode and the nozzle is 1 cm. A glass tube is placed in front of the syringe nozzle at distance d variable from a few millimeters to several centimeters. When HV pulsed dc voltage (amplitudes up to 10 kV, repetition rate up to 10 kHz, and pulse width variable from 200 ns to dc) is applied to the HV electrode and helium gas is injected into both the hollow barrel and the glass tube with flow rates of 2 and 3 l/min, respectively, two homogeneous helium plasma plumes are generated in the surrounding air as shown in Fig. 1(b).

The applied voltages and the currents are measured by a P6015 Tektronix HV probe and a TCP202 Tektronix current probe, respectively. A fast intensified charge-coupled device (ICCD) camera (Princeton Instruments, Model PIMAX2, exposure time down to 0.5 ns) is used to capture the dynamics of the discharge. The exposure time is set to 1 ns for all the photographs shown in this paper. A spectrometer (Princeton Instruments Acton SpectraHub 2500i) is used to measure the emission spectra of the plasma. The entrance and the exit slits of the spectrometer are fixed at 100 μm for the experiment reported in this paper. A grating of 1200 grooves/mm is used for all the spectrum measurements.

III. EXPERIMENT RESULTS

The current-voltage (I-V) characteristics of the discharge are shown in Fig. 2, where V_a is the applied voltage and I_{dis}

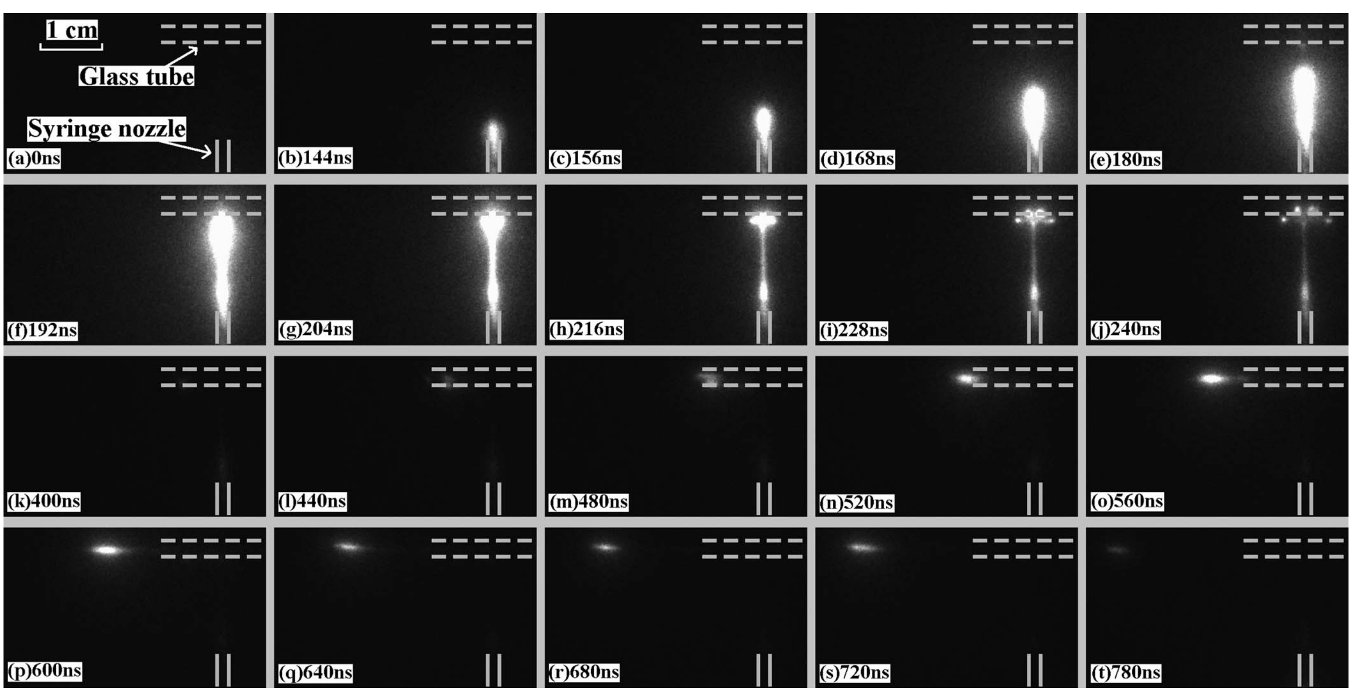

FIG. 3. High-speed photographs of the plasma plume. The exposure time is fixed at 1 ns. The time labeled on each photograph corresponds to the time in Fig. 2.

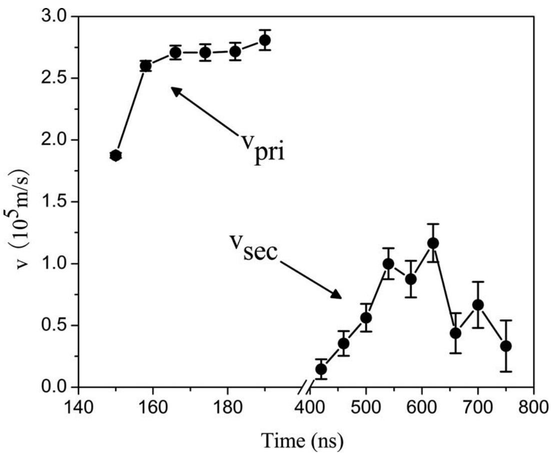

FIG. 4. The propagation velocities of both the primary v_{pri} and the secondary v_{sec} plasma plumes vs time.

is the actual discharge current, which is obtained by subtracting the displacement current from the total current. Two discharge current pulses per applied voltage are observed. This is similar with that observed in the pulsed dielectric barrier discharge.[35]

In order to avoid the direct interaction between the primary and the secondary gas flows, a ring-shaped barrier is attached to the outer surface of the glass tube as shown in Fig. 1(a). It is found that the barrier does not affect the ignition of the secondary plasma plume. Therefore, the ignition of the secondary plasma is not due to the interaction of the two gas flows.

To investigate how the secondary plasma plume is ignited, the ICCD camera is used to capture the dynamics of the discharge. Figure 3 shows the photographs of the discharge taken at different delay times. Each picture is an integrated image of over ten shots with the same delay time. According to Figs. 3(b)–3(f), the primary discharge resembles a cathode-directed streamerlike discharge, which propagates from the syringe nozzle to the glass tube. The luminance of the primary plasma decreases quickly upon approach to the wall of the glass tube. At about 440 ns, a weak luminous plasma is ignited inside the glass tube as shown in Fig. 3(l). The plasma propagates, reaches the open end of the glass tube, and becomes brighter at 520 ns, as shown in Fig. 3(n). Then the plasma continues propagating for about 200 ns before it dies out. The details on the propagation velocities of the primary and the secondary plasmas are plotted in Fig. 4. Due to the small fluctuation of the plasma bullet location, we repeated the experiment six times. The error bar of the bullet velocity is calculated based on the six experiments. It clearly shows that the velocities of the primary plasma are several times higher than that of the secondary plasma. It should be emphasized that the secondary plasma is ignited at about 200 ns after the primary plasma is extinguished. The ignition mechanism of the secondary plasma will be discussed in Sec. IV.

To characterize the plasma plumes, the emission spectra of the primary and the secondary plasma plumes have also been measured. Figure 5 shows the typical emission spectra of the secondary plasma plume. It shows that the spectra of the plume are dominated by the excited OH, N_2, N_2^+, He, and O species. To save space, we only show the emission spectra of the secondary plasma plume here. The emission characteristics of the primary plasma plume are quite similar with that of the secondary plume. However, the emission intensities of all the lines from the primary plume are several times higher than that of the secondary plume. In addition, the rotational and vibrational temperatures, two of the important parameters of the nonequilibrium plasmas, can also be obtained from the emission spectra of the plasmas. To estimate the rotational and vibrational temperatures of both plasmas, the simulated spectra of the $C\,^3\Pi_u - B\,^3\Pi_g(\Delta v = -2)$ band transition of nitrogen are compared to the measured spectra. The rotational and vibrational temperatures are obtained when the best fits are achieved.[36] Figure 6 shows that both plumes have the rotational and vibrational temperatures of 300 and 2500 K, respectively.

IV. DISCUSSION

As was reported before,[20] a human hand can touch any part of the primary plasma plume without any harm. Thus the voltage along the primary plasma plume is probably low. Therefore the applied voltage cannot ignite the secondary plume, but the photon emission from the primary plasma and the local electric field created by the charges deposited on the glass tube surface may be able to ignite the secondary plasma. However, when the glass tube is replaced by an alumina tube or a quartz tube, we are also able to generate the

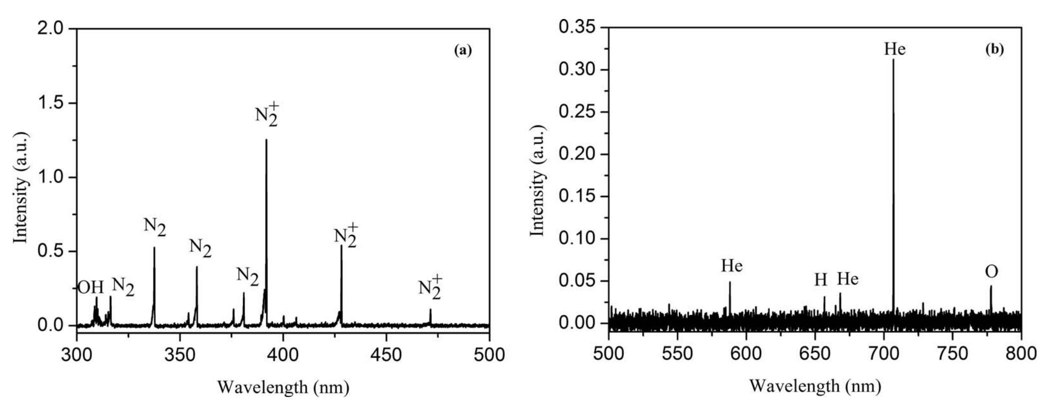

FIG. 5. The emission spectra of the secondary plasma plume. The discharge conditions are the same as in the photograph of Fig. 1(b)

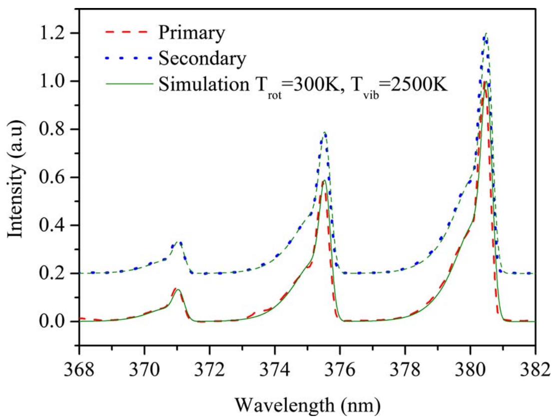

FIG. 6. (Color online) The simulated and the measured primary and secondary plasma plumes spectra of N_2 second positive system 0–2 transition. The curves were intentionally shifted vertically for better separation. Two simulated spectra (one is intentionally shifted vertically) are for the same rotational and vibrational temperatures.

secondary plume with no obvious difference. Therefore, the photons emitted by the primary plume play no direct role in the ignition of the secondary plume. The other possible source is the local electric field created by the charges deposited on the glass tube surface. The charges Q deposited on the glass tube surface can be obtained by integrating the plume current, which has a peak current of about 300 mA.[20] By integrating the plume current, the charges deposited on the glass tube surface is obtained to reach a peak value of about 10^{-8} C. Assuming that the charges are equally distributed along an ideal ring with infinitesimal width on the glass tube surface, the electric field along the glass tube can be calculated according to simple electrostatics. The maximum electric field inside the glass tube can reach more than 20 kV/cm, which is higher than the breakdown voltage of helium at atmospheric pressure. Therefore, the charges deposited on the glass tube surface can indeed ignite the plasma.

Based on the ignition mechanism of the secondary plasma discussed above, the propagation of atmospheric pressure plasma jets can be attributed to the local electric field induced by the charges in the bulletlike volume. Besides, the external electric field from the applied voltage due to the relatively low but not negligible conductivity of the dark track left by the plasma bullets will add to local electric field and favor the propagation of the plasma bullet.

V. CONCLUSION

In conclusion, a helium plasma plume generated in the ambient air (primary plasma), which propagates through the wall of a dielectric tube and keeps propagating in the tube (secondary plasma), is reported. Detailed studies on the ignition mechanism of the secondary plasma show that the charge Q calculated from the measurement of the primary plume current can reach its maximum of about 10^{-8} C. These charges can induce a maximum electric field of more than 20 kV/cm. Therefore, the induced electric field may be responsible for the ignition of the secondary plasma, which indicates that the propagation of the plasma plumes may be due to the local electric field induced by the charges in the bulletlike plasma volume.

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