

## Are all atmospheric pressure cold plasma jets electrically driven?

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(Received 13 October 2011; accepted 5 March 2012; published online 23 March 2012)

Up to now, all studies on the dynamics behavior of non-equilibrium plasma plumes were focussed on noble gas plasma plumes. It was found out that they are electrically driven rather than gas flow dependent. Our study on the dynamics of a non-equilibrium N<sub>2</sub> plasma plume reveals that the propagation velocity of the N<sub>2</sub> plasma plume is several orders magnitude lower than those previously reported and further studies show that it is close to the gas flow velocity. The gas flow has a significant effect on the length of the plasma plume, and the results provide some fundamental knowledge about atmospheric pressure plasma jets. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.3696889>]

Atmospheric pressure cold plasmas are receiving increasing attention due to applications in surface and materials processing, biomedical engineering, and medicine.<sup>1–10</sup> In biomedical applications such as sterilization employing atmospheric pressure non-equilibrium plasma jets (APNP-Js), the plasmas are generated in open air rather than in confined discharge gaps as in traditional dielectric barrier discharge (DBD) devices.<sup>11–19</sup> Hence, they can be used in direct treatment and there is no limitation on the size of the objects to be treated. APNP-Js produce plasma plumes with lengths from a few millimeters to more than ten centimeters. The dynamics of plasma plumes appears to be continuous visually and it propagates at a high speed resembling a bullet.<sup>20–44</sup> It is generally accepted that the propagation is electrically driven rather than gas flow dependent. The model proposed by Lu and Laroussi assumes that the local electric field and photon-ionization play an important role in the propagation.<sup>21</sup> Lu *et al.* suggested that the local electric field induced by charges in the plasma was crucial to the propagation<sup>22,23</sup> and Li *et al.* observed that when the plasma plume propagated in air, penning ionization affected the propagation dynamics.<sup>24</sup> This is also consistent with the ring-shaped emission profile observed from plasma bullets.<sup>25–28</sup> Karakas *et al.* studied the correlation between the helium mole fraction and plasma propagation<sup>29</sup> and observed that plasma propagation was inhibited, if the ratio of air molecules to helium atoms exceeded a certain value. Park *et al.* and Jarrige *et al.* believe that plasma bullets are ionized waves.<sup>26,30</sup> Sands *et al.* found that plasma plume initiation preceded the discharge between the two ring electrodes in the tube.<sup>31,32</sup> Naidis simulated the plasma plume behavior by two streamer models.<sup>33,34</sup> One model assumes that the plasma plume propagation channel is highly pre-ionized and the other one assumes that there are photo-ionization effects. The simulation results from both models show that local electric field

plays an important role in the propagation. The propagation velocities derived from the two models are similar and on the order of 10<sup>5</sup> m/s. All in all, previous reports point to that plasma plumes generated by APNP-Js are electrically driven and propagate at a speed of 10<sup>4</sup> to 10<sup>5</sup> m/s. However, is this mechanism true for all types of non-equilibrium plasma plumes? In this work, a custom designed APNP-J was used to generate non-equilibrium N<sub>2</sub> plasma plumes up to 2 cm long to investigate the propagation dynamics, and our results disclose the phenomenon that it is driven by gas flow instead of electric field.

Figure 1 depicts the schematic of the device together with a photograph showing the N<sub>2</sub> plasma plume. The plasma jet is made of a quartz tube with an inner diameter of 1 mm, and a stainless steel needle with a diameter of 0.2 mm is placed in the center of the quartz tube to serve as the high voltage (HV) electrode. A copper ring with a diameter of 1 mm is placed next to the front end of the quartz tube to serve as the ground electrode. The distance between the HV electrode and ground electrode is about 2.5 mm and the HV electrode is connected to a DC power supply *via* a 20 MΩ resistor. The DC power is adjustable up to 20 kV. When N<sub>2</sub> flows through the quartz tube and the HV power supply is on, a cold plasma plume is generated in the surrounding air with a length of up to about 2 cm as shown in Fig. 1. The gas flow rate is estimated to be about 126 m/s. The voltage on the HV electrode is measured by a HV probe (Tektronix P6015), the current by a Pearson 2877 current probe, and recorded by a wideband oscilloscope (Tektronix: DPO7104).

Figure 2 show the current-voltage characteristics of the discharge. The discharge occurs periodically at a frequency of several kHz. As shown in the waveforms of a single pulse in Fig. 2(b), the discharge current lasts for about 15 ns with a peak value of about 4 A. During the discharge, the voltage on the needle drops to 0 V.

When a grounded steel cone is placed several millimeters away from the plasma jet nozzle, the N<sub>2</sub> plasma plume does not stop propagating and flows around the steel

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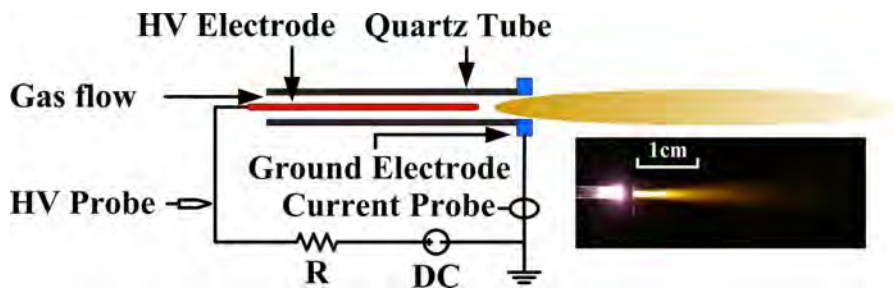


FIG. 1. Schematic of the plasma jet together with a photograph on the right showing the non-equilibrium  $N_2$  plasma plume ( $R=20\text{ M}\Omega$ , applied voltage  $V=10\text{ kV}$ , and  $N_2$  flow rate = 5 SLM).

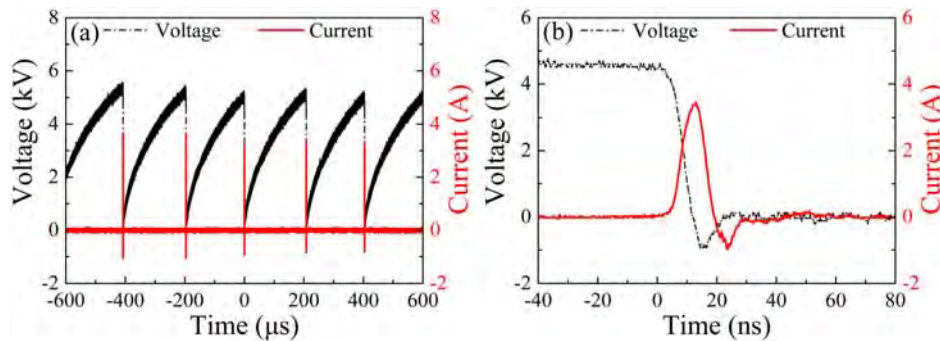


FIG. 2. Voltage and current characteristics of the discharge: (a) Multiple pulses and (b) Single pulse.

cone as shown in Fig. 3. The steel cone does not affect the discharge current or voltages nor does it have any effects on the intensity of the plasma plume. The observation is different from that reported before and shown in Fig. 4.<sup>16</sup> The device in Fig. 4 consists of a HV wire electrode inserted into a quartz tube with one closed end. The quartz tube along with the HV electrode is inserted into the hollow barrel of a syringe. When He is injected into the hollow barrel as a flow rate of 2 l/min at a pulsed DC HV voltage of 6 kV, repetition rate of 10 kHz, and pulse width of 500 ns, a 3 cm long cold He plasma plume is generated as shown in Fig. 4(a). When the grounded steel cone is placed close to the plasma plume (but not in direct contact), the plasma plume bends towards the cone-shape steel and stops propagating as shown in Fig. 4(b). It can be explained by that the plasma plume in Fig. 4 is electrically driven. The grounded steel cone close to the plasma plume affects the electric field distribution and consequently propagation of the plasma plume. The plasma plume also stops at the steel cone even, if it is grounded *via* a resistor of several  $M\Omega$ . On the other hand, with regard to the  $N_2$  plasma plume generated by the device as shown in Fig. 1, when a grounded steel cone is placed in contact with the plasma plume similar to that shown in Fig. 4(b), propagation

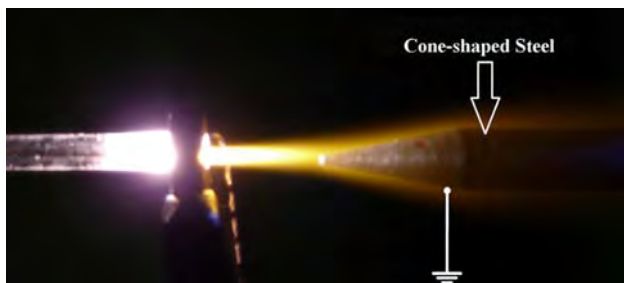


FIG. 3. Photograph of the plasma plume with a grounded steel cone placed in front of the plasma plume. The plasma plume flows around the cone.

of the  $N_2$  plasma plume is not affected at all. Therefore, the propagation mechanism must be different and is perhaps not electrical driven.

To investigate whether the plasma plume dynamics is dictated by another factor such as the gas flow velocity, a fast intensified charge-coupled device (ICCD) camera (Princeton Instruments, Model: PIMAX2, exposure time down to 0.5 ns) is employed to capture the dynamics of the discharge. The exposure time is set to 5  $\mu\text{s}$  for all the photographs taken at different time in Fig. 5. The ICCD camera is triggered by a discharge current of 3 A. Each picture is an integrated picture of over 50 shots with same delay time. According to Fig. 5, the plasma leaves the nozzle 1  $\mu\text{s}$  after the discharge ignites and the plasma plume indeed resembles a bullet.

The plume propagation velocity is plotted versus time in Fig. 6. Because the actual plume location fluctuates slightly *albeit* for same delay time, five shots are taken for each delay time. The initial propagation velocity is about 180 m/s and

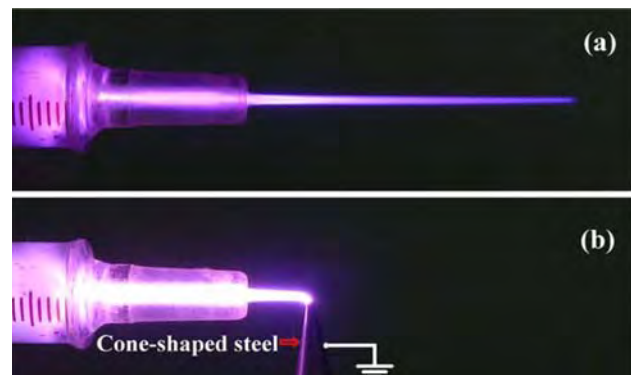


FIG. 4. Photographs of a He plasma plume: (a) The plasma plume propagates in ambient air freely. (b) A steel cone close to the plasma plume stops the propagation.

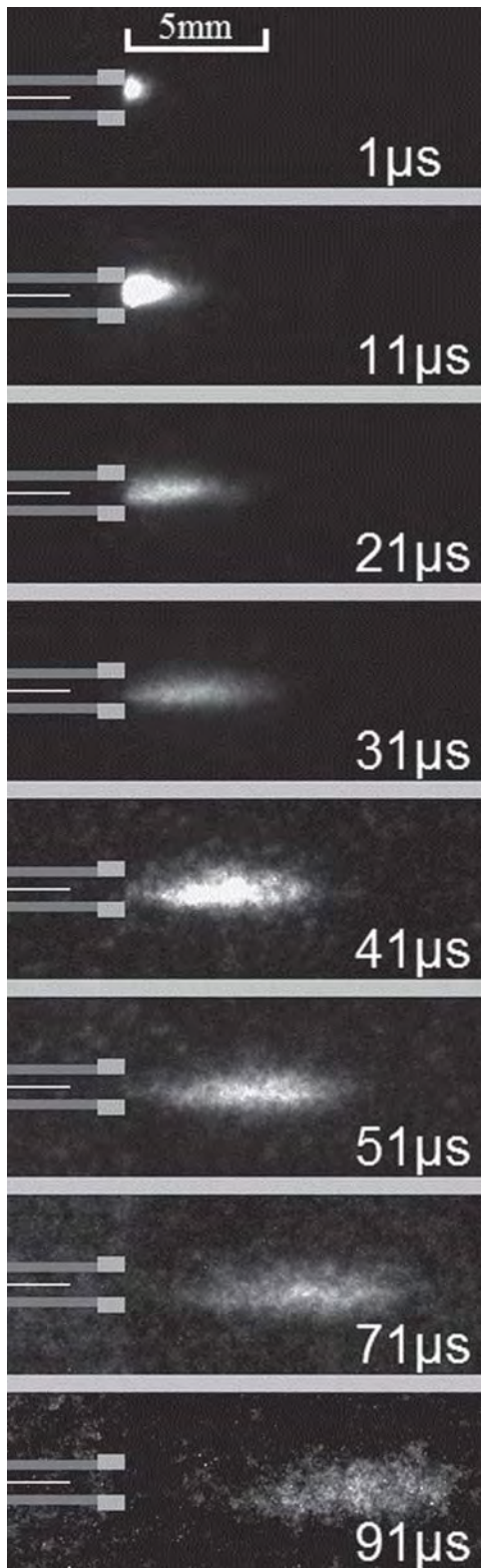


FIG. 5. Photographs of the plasma plume taken by a high speed camera at an exposure time of  $5 \mu\text{s}$ .

decreases with time dropping to about  $80 \text{ m/s}$  after  $80 \mu\text{s}$ . The velocities are several orders of magnitude lower than those noble gas operated jets reported and are in fact close to the estimated gas flow velocity. In the beginning, the propagation velocities are slightly higher than the gas flow velocity, probably due to air diffusion into the  $\text{N}_2$  channel.

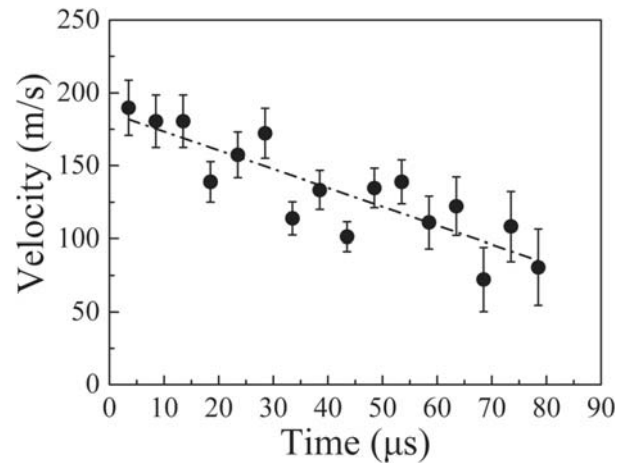


FIG. 6. Velocity of the plasma plume versus time.

Because the ionization energy of  $\text{O}_2$  is smaller than that of  $\text{N}_2$ , some excited state  $\text{N}_2$  such as  $\text{N}_2(\text{C})$  states have energy closer to the ionization energy of  $\text{O}_2$ , and so they may affect the plasma propagation. Only a small  $\text{O}_2$  concentration may deliver this effect because too much of  $\text{O}_2$  will result in the attachment. More work is needed to elucidate the exact mechanism.

If the plasma plume is governed by the gas flow, the gas flow rate should affect the length of the plasma plume. Fig. 7 displays the photographs of the plasma plume taken at different gas flow rates. The results clearly show that the lower the gas flow rate, the shorter is the plasma plume, and the relationship is almost linear. This provides evidence that the dynamics of the  $\text{N}_2$  plasma plume depends on the gas flow.

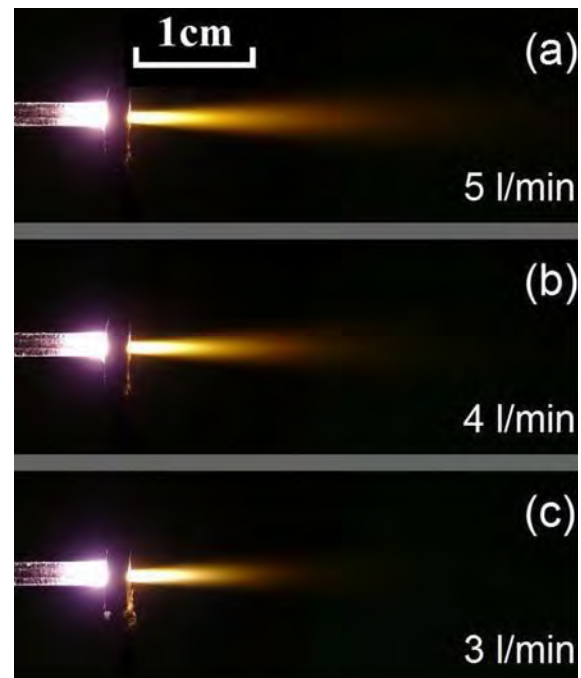


FIG. 7. Photographs of the plasma plume taken at different gas flow rates at an applied voltage of  $10 \text{ kV}$ .

This work was partially supported by the National Natural Science Foundation (Grant Nos. 10875048 and 51077063), Research Fund for the Doctoral Program of Higher Education of China (20100142110005), Chang Jiang Scholars Program, Ministry of Education, People's Republic of China, and Hong Kong Research Grants Council (RGC) Special Equipment Grant (SEG) No. SEG\_CityU05.

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