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Atmospheric pressure He-air plasma jet: Breakdown process and propagation phenomenon

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In this paper He-discharge (plasma jet/bullet) in atmospheric pressure air and its progression phenomenon has been studied experimentally using ICCD camera, optical emission spectroscopy (OES) and calibrated dielectric probe measurements. The repetitive nanosecond pulse has applied to a plasma pencil to generate discharge in the helium gas channel. The discharge propagation speed was measured from the ICCD images. The axial electric field distribution in the plasma jet is inferred from the optical emission spectroscopic data and from the probe measurement. The correlation between the jet velocities, jet length with the pulse duration is established. It shows that the plasma jet is not isolated from the input voltage along its propagation path. The discharge propagation speed, the electron density and the local and average electric field distribution along the plasma jet axis predicted from the experimental results are in good agreement with the data predicted by numerical simulation of the streamer propagation presented in different literatures. The ionization phenomenon of the discharge predicts the key ionization parameters, such as speed, peak electric field in the front, and electron density. The maximum local electric field measured by OES is 95 kV/cm at 1.3 cm of the jet axis, and average EF measured by probe is 24 kV/cm at the same place of the jet. The average and local electron density estimated are in the order of 1011 cm−3 and it reaches to the maximum of 1012 cm−3. © 2013 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution 3.0 Unported License.

I. INTRODUCTION

Over the years various kind of non thermal plasma jets like dielectric barrier plasma pencil, double electrode plasma pencil, and single electrode plasma pencil driven by RF, Pulsed DC, unipolar, bi-polar power supply have been developed. This Non-thermal Atmospheric Pressure Plasma Jet’s (NAPPJ) immerged in the open air can be used in wound healing,1 sterilization,2 and nano-structure fabrications.3 Over the last decade, the Non-thermal Atmospheric Pressure Plasma Jet’s (NAPPJ) propagation and reaction mechanism within its active constituents in the ambient air have been extensively studied, both experimentally and theoretically. Although there are clear similarities with atmospheric pressure streamer propagation mechanism with the plasma jet propagation, the energy transfer inside the proliferating plasma bullet/jet are not clear yet. Some of the recent experimental works on the jet propagation are presented in Refs.4–11. In explaining the propagation of the plasma jet front, the front velocity is taken as an important parameter. Recent experimental results as of the ICCD imaging and optical emission spectroscopy shows that the discharge starts from the surface of the plasma jet generators outlet,12,13 which gives an impression that the plasma jet propagation
might be the propagation of the surface wave, but the propagation of the plasma jet in the open air does not show any resembles with the surface wave propagation. Dr. Laroussi and Xin Pei Lu considered this plume as a positive streamer and used Dawson and Win's model for positive streamer propagation in low electric field to describe its propagation nature and expansion dynamics. Most of the studies about streamer propagation considering photoionization are done under the effect of external electric field. In weak electric field region, streamer head Electric Field (EF) and the photoionization play an important role in streamer propagation dynamics.

Shi et al. invoked an ionization wave propagation model to explain the plasma bullet propagation. It is also predicted that the high velocity of the plasma front is due to the ponderomotive force, electron diffusion, and breakdown wave in the feed gas channel. In the ionization wave propagation model, the gas breakdown mechanism is the same as the breakdown mechanism in streamer. The difference between the streamer discharge and the ionization wave discharge is that the later one shows the high spatial uniformity and reproducibility. In both types of discharges, the key elementary processes controlling the discharge propagation are the impact ionization and the photoionization in the discharge front. Some recent experimental results showed the spatial evolution of the discharge and propagation velocity of the plasma jet in the open air. Due to the small dimension and high propagation speed, detailed measurements and characterization of the NAPPJ are experimentally difficult. Numerical simulation has been used to understand the dynamics of the discharge front in the helium plasma jet. Jaskeky et al. investigated the atmospheric pressure air discharge generated by needle anode and found that the plasma behind the front have two modes. In our last paper we have shown that the discharge initiates near the high voltage electrode and expands in the open air with the speed of 2-10 cm/ns.

In this paper the plasma bullet/jet’s propagation dynamics for different operating conditions are investigated. The experimental investigation of the plasma jet propagation was done by using ICCD imaging, optical emission spectroscopy, and by a dielectric probe technique. The spatial evolution of the plasma jet’s velocity is measured for different operating conditions. A relation between the applied voltage’s pulse duration with the jet length and the plasma jet’s velocity is established. The change of the Electric Field (EF) along the jet axis is investigated. These results are compared with the propagation dynamics of the streamer and the ionization wave propagation. The possibility of the transition of the streamer discharge to the ionization wave discharge is also analyzed by analyzing the experimental data.

II. EXPERIMENTS

The plasma pencil is the plasma bullet/jet generator used to generate plasma and this plasma comes out from its chamber through the outlet following the helium gas channel in to the ambient air. The plasma pencil used in this experiment contains two dielectric disks with 3 mm hole at their centers, which are placed in a dielectric tube. The outer surface of a disk is attached to a grounded copper ring electrode. The copper ring attached to the outer surface of the inner disk is connected to a pulsed high voltage source. The plasma pencil is operated with high voltage pulse within 4-8 kV, pulse width ranging from 500 to 800 ns, and a frequency of 4 kHz. The outlet at the dielectric barrier is used as the reference position of the jet (z = 0).

The gas flowing through the plasma pencil is ignited by applying a high voltage to generate plasma jet. This plasma pencil was operated by a DFI PVX-4110 pulse generator whose input voltage is supplied by a Spellman SL 1200 high voltage power supply. This power supply can generate maximum 10 kV output voltage. Bronkhorst digital mass flow meter is used to control the gas flow rate to the plasma pencil. To investigate the electrical characteristics of the plasma jet generated by the plasma pencil, Tektronix TDS784D oscilloscope, Tektronix TMS502A current amplifier and current probe, and Tektronix P6015A high voltage probe were used. All the electric measurements were taken with an average of 500 acquisitions. The emission spectrum of the plasma jet is acquired by using Spectra pro-500i spectrometer. It includes two 1200 groves per millimeter grating and its scan range is 0-1400 nm with the minimum step of 0.0025 nm. An ICCD ultra fast camera was used to capture the images of the plasma jet in nano-second exposure. Plasma jet velocity along the jet axis was measured from the images captured by an ICCD camera, whose exposure time
was set 20 ns with 20 ns delay. From the time and the jet’s front position, the plasma jet’s velocity was measured along the jet axis. These measurements were done for different operating conditions. The schematic of the experimental set-up is shown in Figure 1.

A plasma jet is a discharge of flowing helium in the ambient atmosphere. The working gas is the mixture of helium with air, and air contains nitrogen and oxygen. The presence of nitrogen and oxygen in the helium channel changes the plasma chemistry and the degree of ionization. To get the local reduced electric field (REF) of the plasma jet along the jet axis, the intensity ratio of the two nitrogen bands was used as in Refs. 31–34. Bolsig+ solves the Boltzmann equation to determine the electron energy distribution function using a given cross section of all gas species and determine the electron transport coefficients and the reaction rate constant. Bolsig+ simulation tool was used to find the excitation and ionization rate of the different species in the plasma jet for different percentage of the air mixing with the helium gas.

The experimental setup to measure the jet current by using dielectric probe is shown in Fig. 2. The spatial evolution of the jet current and the jet electron density are calculated from the jet current of the plasma bullet at different positions along the jet axis as in Ref. 30. The jet’s radius at different position on the jet axis is measured from the image of the plasma jet. Using the same procedure as in Ref. 30, the current density and the approximate average electric field along the jet axis are estimated, and this electric field is compared with the estimated local EF found by using ratio method.

III. RESULTS
A. Measurement of the Jet Velocity

The plasma jet velocity is the expansion of the plasma with time in the air. It is measured from the change of the jet front’s position and required time for this change. The position and the time were indentified from the ICCD image of the plasma jet. The jet velocity for different Applied Voltages (AV), Pulse Widths (PW), and Gas Flow Rates (GFR) are shown in Fig. 3. The velocity curve of the plasma jet along the jet axis shows three distinct phases of the plasma bullet/jet: i) transition phase,
FIG. 2. Experimental set up for the jet current measurement by using dielectric probe.

FIG. 3. Plasma bullet velocity along the axis for different pulse widths measured from the ICCD image of the plasma jet for every 40 ns: a) for different applied voltages along the jet axis (PW 500 ns, GFR 3.2 l/min), b) for different pulse widths, c) for different GFRs at the operating applied voltage of 5 kV and pulse width of 500 ns.
ii) propagation phase, and ii) collapse of the plasma jet. Kong and his group also found three notable modes in plasma jet. Along the transition phase, the plasma jet’s velocity increases from the reference point \((z = 0 \text{ cm})\) to a certain distance from the outlet; where the propagation phase in the plasma jet’s velocity curve is due to the propagation of the plasma jet with slowly decreasing velocity in the ambient atmosphere along the jet axis. It starts from the end point of the transition phase of the plasma jet. The velocity of the plasma jet is strongly oscillatory along the propagation phase. At the end of the pulse width, the jet velocity decreases rapidly and the plasma jet dies away. This abrupt decay of the plasma jet’s velocity is due to the collapse of the plasma jet. The very reason that the Plasma jet collapses at the end of the pulse clearly indicates that jet propagation is strongly dependent on the applied voltage. All three phases of the plasma jet velocity curve are explained in this section.

The plasma jet velocity curve for different applied voltages \((PW = 500 \text{ ns}, \text{GFR} = 3.2 \text{ l/min})\) along the jet axis measured from the ICCD images of the plasma jet for every 40 ns is shown in Fig. 3(a). At the beginning, it shows that the plasma jet velocity for different applied voltages increases with applied voltage along the transition phase. This velocity reaches its maximum within 0.85 cm and 1.5 cm of the jet axis. The end point of the transition phase moves towards the left with the increase of the applied voltage. It gives the notion that the propagation phase of the plasma jet starts closer to the outlet for a higher applied voltage. The length of the propagation phase and the velocity of the plasma jet along this phase increases with the applied voltage. The collapse of the plasma jet starts at the end of the propagation phase.

The velocity change of plasma jet is almost the same along the transition phase for the change of the pulse width (Fig. 3(b)). The length of the propagation phase increases with pulse width and at the end of this phase, the plasma jet’s velocity shows an abrupt decay like previous velocity curves. The change of the plasma jet velocity with different GFRs \((AV - 5 \text{ kV}, PW - 500 \text{ ns})\) along the jet axis is shown in Fig. 3(c). Along the transition phase, the plasma jet velocity is highest for the gas flow rate of 2.36 l/min. The plasma jet velocity along this phase is decreasing for the GFR above 2.36 l/min. The propagation phase of the plasma jet velocity curve ends within 1.0 cm and 1.75 cm of the jet axis for all GFRs (within 2.36-8.0 l/min). The length of the propagation phase for the GFR of 2.36 l/min is long compare to the length of the propagation phase for the feed GFR above 2.36 l/min. The propagation velocity is lower for the shorter propagation phase.

The experimental results show that for longer jets, the plasma bullet velocity reaches higher value and opposite happens to the shorter plasma jet. The charged particles and the excited molecules (especially helium) come out from the discharge chamber and at the outlet of the plasma pencil it ionizes and excites nitrogen and oxygen in air. As the ionization energy of nitrogen is lower than the ionization energy of helium, there will be enhanced plasma chemistry close to the outlet in the ambient air because of the metastable helium (excitation energy of helium is 24 eV) and the effect of the applied electric field. The electric field and the number density of metastable helium at the outlet of the plasma pencil increases with applied voltage, so the ionization process increases and the plasma bullet velocity increases along the transition phase. The transition phase of the plasma bullet velocity curve for these operating conditions end almost at the same position and it is within 1.0 - 1.75 cm of the jet axis from the outlet of the plasma pencil. The propagation phase of the plasma bullet is quasi stationary velocity phase. Experimental investigation shows that in general, the length of the propagation phase is longer when the changing rate of the plasma bullet velocity along the transition phase is higher. This indicates that the plasma property of the plasma bullet during the transition phase influences the propagation of the plasma bullet. Higher input energy creates more energetic plasma bullet in the transition phase, which can propagate a longer path along the jet axis. A moving avalanche to the streamer transition took place earlier for higher applied voltage after the discharge coming out in the ambient air.

### B. Correlation between the Pulse duration, Jet’s Velocity, and the Jet’s Length

For different applied voltages, plasma jet collapses at different positions on the jet axis but for a constant pulse width it collapses at the same time. Even though the length of the plasma jet depends on the applied voltage and the gas flow rate, the total propagation time is strongly pulse
width dependent. If there is a correlation between the length of the plasma jet and the pulse duration, there must be a correlation between the length of the plasma jet and the velocity of the plasma jet. In this section we have established a relation between the pulse duration, jet’s velocity and jet’s length. Figure 4 shows the correlation between the average plasma jet velocity and the length of the plasma jet. The average plasma jet velocity is calculated by taking the average of the velocity from the generation of the plasma jet at the reference point to the end of its propagation phase. The average propagation velocity of the plasma jet is the average plasma jet velocity only along the propagation phase. The average propagation velocity is much higher than the average plasma jet velocity \( v_{av} \). Figure 4(a) shows that the average plasma jet velocity and the average propagation velocity increase with the length (or AVs) of the plasma jet. The plasma-jet length for different AVs measured from the image of the plasma jet is also shown in Fig. 4(a). The average plasma jet length \( l_{cal} \) is calculated by multiplying the pulse width \( \tau_{pw} \) with the average plasma jet velocity \( l_{cal} = \tau_{pw} \cdot v_{av} \). Plasma jet length = plasma jet velocity \( \times \) pulse duration. The measured jet length is compared with this average plasma jet length \( l_{cal} \). It shows that the measured jet length is almost the same as the calculated average jet length.

Figure 4(b) presents the change of the length of the plasma jet and the average plasma jet velocity with voltage pulse duration. The length of the plasma jet increases almost linearly with the pulse width ranges from 400 ns to 700 ns. For different pulse widths the average plasma jet velocity curve follows the same trend as the length of the plasma jet. The average propagation velocity increases with pulse width and is higher than the average plasma jet velocity. The measured plasma jet length is compared with the calculated average jet length and it is found that within the low pulse width range (400-650 ns), the measured jet length is almost the same as the calculated average jet length.

Figure 4(c) shows the change of the average plasma jet velocity and the length of the plasma jet with different GFRs (within 1.04-8.0 l/min). The average plasma jet velocity and the average propagation velocity increase from the GFR of 1.04 l/min to the GFR of 2.36 l/min. Similar to
FIG. 5. a) Spatial evolution of the different excited species of nitrogen in the plasma bullet for two different applied voltages, and b) Spatial evolution of emission intensity from the excited helium and atomic oxygen for two different applied voltages (5 kV and 6 kV).

The average velocity curve of the plasma jet, the length of the plasma jet also increases from the GFR of 1.04 l/min to the GFR of 2.36 l/min. The measured plasma-jet length, the average plasma bullet velocity, and the average propagation velocity decrease when the feed GFR is above 2.36 l/min. The calculated plasma-jet length curve also shows the same trend as the measured plasma-jet length. For the GFR above 2.36 l/min, it does not show prominent difference between the calculated plasma-jet length and the measured jet length. The difference between the calculated jet length and the measured jet length decreases with the increase of the GFR.

The calculated length from the average velocity of the plasma jet and the pulse width shows that there is a correlation between the length of the plasma jet and the operating voltage pulse duration. The calculated average length of the plasma jet is little long compare to the measured length of the plasma jet. The actual calculated length of the plasma jet will be the product of the average plasma bullet’s velocity and the pulse duration after subtracting the formation time of the plasma bullet, and this will be smaller than the calculated length of the plasma jet presented here. It is found that in the ionization wave discharge, discharge length changes with the applied voltage’s pulse duration. It also can be said that the plasma jet outside the plasma pencil is not isolated from the applied voltage source. The discharge initiates from the HV source, propagates towards the grounded electrode and comes out through the outlet at the grounded dielectric disk. The length of the plasma jet depends on the feed gas flow rate, applied voltage and pulse duration. Jet propagation velocity also changes with all these parameters, but the duration of the jet’s life is the same as the pulse duration.

C. Optical Emission Spectroscopy of Plasma Jet

The emission spectrum from the excited plasma species and the excitation process of the atom and molecules in the plasma jet are shown in Refs. 4 and 13. The intensity of the different species in the plasma jet for different operating conditions is presented in different literatures.36, 37 Here, the spatial evolution of the relative emission intensity of different species for different operating conditions is presented to identify the different transition points in the plasma jet. These results are compared to the jet propagation velocity curve.

It is found that the most intense emissions are from the excited nitrogen and helium.4 Besides that, atomic oxygen and hydroxyl ions are also present in the plasma. The intensity of the different species increases with applied voltage. The spatial evolution of the intensity of the excited nitrogen for two different applied voltages is shown in Fig. 5. The intensity of the 390.8 nm emission line increases from the starting of the plasma bullet and reaches to its peak when the plasma bullet is at within 0.6 cm and 1.5 cm of the jet axis. After this position, the intensity of 390.8 nm emission line decreases slowly. For the applied voltage of 5 kV, the intensity of the emission line of 336.6 nm wave length increases from the starting of the plasma bullet following the same trend as the intensity of the emission line of 390.8 nm wave length until 0.9 cm of the jet axis, and reaches
to its peak at 2.2 cm of the jet axis. For the applied voltage of 6 kV, the intensity of the emission line of 336.6 nm wavelength from the plasma bullet reaches to a maximum around 0.6 cm of the jet axis and maintains an almost steady state intensity value until 3.0 cm of the jet axis. The intensity of the emission line at 706 nm wave length increases from the reference position and reaches to its peak around 1.2 cm of the jet axis. For the applied voltage of 5 kV, this intensity decreases linearly until the end of the plasma jet. For the applied voltage of 6 kV, the intensity is almost constant until 1.8 cm of the jet axis and then decreases linearly. The intensity of the emission line of 777.4 nm wave length does not show prominent difference for these two applied voltages.

For a laminar feed gas flow rate (3 l/min), the intensity of the emission line of 390.8 nm and 706 nm wavelengths reaches to its maximum with in 0.9 cm and 1.5 cm of the jet axis (Fig. 6). The emission intensity of 336.6 nm emission line reaches to its peak far from the maximum intensity of 390.84 nm emission line. It is because the excitation energy of $\text{N}_2^+$ (B) (18.5 eV) is higher than the excitation energy of $\text{N}_2$ (C) (11.0 eV). The change of the intensity of the different species along the jet axis depends on the gas mixture. For the gas flow rate of 6.8 l/min, the feed gas flow is turbulent, so the intensity curve of the different species in the plasma bullet is not in the same shape as the the intensity curve for the gas flow rate of 3.0 l/min.

In the previous section, it was found that the transition phase of the plasma jet end within 1.0 cm and 1.8 cm of the jet axis, and the plasma jet velocity is maximum around that position. There is a correlation between the plasma bullet velocity curve along the transition phase and the emission intensity of metastable helium, excited $\text{N}_2^+$ and $\text{N}_2$. As the excitation energy of helium and $\text{N}_2^+$ are almost the same, the increment of these species along the transition phase is the evidence that the local reduced electric field in this jet region will increase. Along the propagation phase of the plasma bullet, the intensity of the helium and $\text{N}_2^+$ decreases and the intensity of $\text{N}_2$ increases slowly. It seems that the electric field along the propagation phase is not as strong as in the transition phase.

D. Electric Field (EF) and Electron Density Measurement

1. EF measurement by emission spectroscopy

In the estimation of the local Electric Field (EF) of the plasma, spectroscopic method is the most promising technique. The main purpose of this study is to investigate the spatial evolution of the ionized channel in the atmosphere where the effect of applied EF is negligible. For this purpose reduced electric field (REF) along the plasma channel is measured from the intensity ratio of the
FIG. 7. Intensity ratio of nitrogen band along the jet axis for the applied voltage of 6.0 kV with the pulse duration 500 ns: the intensity ratio curve has the similar shape as the plasma bullet’s velocity curve.

molecular spectral bands due to the transition of first negative system (FNS) \([N_2^+ (B)]\)

\[
N_2^+(B^2\Sigma_g^+, v=0) = N_2^+(X^2\Sigma_g^+, v=0) + \frac{hc}{\lambda_B} \quad \lambda_B = 391.5 \, \text{nm}
\]

and second positive system (SPS), \([N_2(C)]\)

\[
N_2^+(C^3\Pi_u, v=0) = N_2^+(B^3\Pi_g, v=0) + \frac{hc}{\lambda_C} \quad \lambda_C = 337.1 \, \text{nm}.
\]

This method is frequently used for electric field strength estimation in nitrogen containing gas discharge plasma. This (0-0) vibrational transition is used for this calculation because they are most widely used in different literatures.\textsuperscript{32, 38–40} Ratio of the intensities of these bands, \(R_{391/337}\) along the jet axis is shown in Fig. 7. The ratio of the intensities of B state and C state of nitrogen shows the similar shape as the intensity of the B state and it is almost the same as the plasma bullet velocity curve. This ratio reaches to its peak within 0.75–1.5 cm of the jet axis.

The \(N_2\) (C) can be populated by the electron impact excitation process from the ground state, associative excitation process and by pooling reactions. There is also stepwise excitation process which increases the number density of C state. The \(N_2(B)\) excited state is possible either by direct electron impact excitation from the ground state or by stepwise excitation processes. This state is also populated by utilizing the internal energy of the metastable helium. Another process which plays an important role to populate \(N_2(B)\) state is the charge transfer reaction with helium atom and nitrogen molecules. In this study, steady state reaction process is considered and it is assumed that the electron impact excitation process is dominant in this optically thin plasma. It is also considered that in the radial direction the ionization by photo-ionization process is negligible. The electron impact excitation process is shown in equation (1). It shows that the excitation rate constant depends
on REF of the plasma jet.

\[
N_2(X^1\Sigma_g^+) + e \rightarrow N_2(C^3\Pi_u, v = 0) + e \quad k_e^{x} = f(E/N)
\]

\[
N_2(X^1\Sigma_g^+) + e \rightarrow N_2^+(B^2\Sigma_g^+, v = 0) + 2e \quad k_e^{b} = f(E/N)
\]  

(1)

The relation between the density of the excited particles and the emission intensity \(I_f\) from those excited particles is determined by the transition frequency \((\nu_{\nu'\nu''})\), the particle’s population at upper level \((N^*)\), the radiative time of the transition \((\tau_0)\), and the probability of the vibrational transition \((A_{\nu'\nu''})\). The intensity,

\[
I_f = h\nu_{\nu'\nu''} \frac{[N^*]}{\tau_0} A_{\nu'\nu''}
\]

\[
A_{\nu'\nu''} = \frac{q_{\nu'\nu''}^3 v_{\nu''}^3}{\sum q_{\nu'\nu''}^3 v_{\nu''}^3}
\]  

(2)

Where, \(q_{\nu'\nu''}\) is the Frank-Condon factor. The depopulation of the excited states occurs due to the spontaneous radiative depopulation and the quenching in the collision with other particles. The change of the excited atoms/molecules’s density with time is determined by subtracting the total number of de-excited molecules form the total number of molecules at the excited state. In steady state condition, the population of the excited molecule/atom does not change with time. The balance equation for the excited particles of nitrogen is,

\[
\frac{d[N^*_2]}{dt} = k_{ex} n_e [N_2(X^1\Sigma_g^+)] - \frac{[N^*_2]}{\tau}
\]  

(3)

To determine the field constant, the time derivation of the excited nitrogen is considered almost zero.

\[
N_2(C^3\Pi_u, v = 0) \rightarrow N_2(B^3\Pi_u, v = 0) + h\nu_{337}
\]

\[
N_2^+(B^2\Sigma_g^+, v = 0) \rightarrow N_2^+(X^3\Sigma_g^+, v = 0) + h\nu_{391}
\]

\[
N_2(C^3\Pi_u, v = 0) + N_2/O_2 \quad \xrightarrow{k_{exc}/k_{ex}} \text{ product}
\]

\[
N_2^+(B^2\Sigma_g^+, v = 0) + N_2/O_2 \quad \xrightarrow{k_{exc}/k_{ex}} \text{ product}
\]  

(4)

For a specific point in the plasma jet, electron density is the same.

The intensity ratio,

\[
R_{391/337} = \frac{I_{391}}{I_{337}} = \left( \frac{\lambda_{337}}{\lambda_{391}} \right) \frac{A_{391}^{sch} g_b k_{ex}^{391}}{A_{337}^{sch} g_c k_{ex}^{337}}
\]  

(5)

Statistical weight (g-function) or the fraction of the excited molecules that radiates, changes with the percentage of the air in the helium. The fraction of the air in the helium channel changes along the axis, so the statistical weight, g-function also changes. The change in the air percentage along the jet axis is approximated as in Ref. 41, where the diffusion of air in helium is calculated by using Comsol Multiphysics for the same helium gas flow rate through the same outlet diameter what we have used in this paper. The air admixture with He-gas channel increases along the jet axis from the outlet of the plasma pencil and at the reference point the air admixture is only 1%.

The electron impact excitation rate constants are determined by solving the Boltzmann transport equation for the gas mixture of helium and air for different reduced electric field. The gas kinetic equation is solved by Bolsig+ Boltzmann solver. It generates a momentum transfer cross-section of all gas species by using the Siglo library.42–44 By using the distribution function one can compute the excitation or ionization rate coefficients. The Bolsig+ program was run for the gas temperature of 300 K. The excitation rate coefficient is a function of reduced electric field and is calculated by solving the Boltzmann kinetic equation. The ratio of the excitation rate coefficients of \(N_2\) and \(N_2^+\) is compared with the experimental results, which gives the reduced electric field in the plasma jet.

Air contains mainly nitrogen and oxygen molecules. A small amount of air can have a major impact on the degrees of ionization, dissociation and attachment rate in the plasma. So, this simulation
FIG. 8. Excitation rate coefficient of the ground state nitrogen to: a) N2(B) and b) N2(C) in different percentage of air mixture with helium.

is run for different air percentage, 1% to 40% of air with feed gas helium. Figure 8(a) shows the rate coefficient of N2 excitation to the N2(C) state for different reduced EF and different amount of air admixture (1%, 5%, 10% and 20%) in the helium. The excitation rate coefficient decreases with the increase of the air in the discharge and increases with the increase of reduced EF. The rate of excitation is higher for the lower percentage of air admixture. The Excitation rate coefficient of nitrogen molecule to the N2 (B) excited state increases linearly with reduced EF (Fig. 8(b)). The rate of excitation to this state is low for the reduced EF below 75 Td. The increment of the excitation rate coefficient is higher for the lower percentage of the air admixture to the helium. For the low reduced electric field range, excitation rate coefficient of N2(C) state higher than the excitation rate coefficient of N2 (B). The excitation rate coefficient is very low for the reduced EF below 50 Td, and this rate coefficient is lower than the rate coefficient of the nitrogen excitation to the B state.

Using these values of the excitation rate in Equ. 5 the intensity ratios of the excited nitrogen (Ic/Ib) were computed. The intensity ratio found from the experimental results was identified in the computed intensity ratio data sheet and the reduced EF for that ratio was branded. This estimated EF along the axis is showed in Fig. 9. The maximum local electric field is 95 kV/cm at the 1.2 cm of the jet axis. It also validates the spatial evolution of the different species of the plasma jet along the axis, specially the intensity of the excited nitrogen (N2 (B)). This maximum local electric field is the same as the measured streamer head potential (100 kV/cm) in Ref. 45.

2. Electrical Measurement of the Electric Field

To measure the Electric Field of the plasma jet, the jet current is measured by using a dielectric probe along the jet axis for every 0.3 cm starting at 0.85 cm from the reference point. During this measurement the operating potential of the plasma pencil was 6 kV. The jet current waveform along the jet axis and the applied voltage pulse are shown in Fig. 10. When the plasma jet reaches the probe, the jet current increases and reaches to the maximum, after that point the current decreases until the end of the pulse. There is a negative jet current pulse at the voltage fall time. This second pulse is due to the secondary discharge of the plasma jet. The current density at any position of the jet is measured from the jet radius at that point of the jet and the positive peak current at that position. Considering this 0.3 cm plasma jet as a uniform plasma column, the EF of this jet segment is estimated as in Refs. 13 and 30.

\[
E = \frac{\text{power density}}{\text{current density}}
\]

The EF of the plasma jet along the axis estimated by using dielectric probe is presented in Fig. 11. This result is compared to the local EF estimated by ratio method (Fig. 11). These curves Show the first increase of the electric field and then it shows a decrease of the EF along the jet axis. The estimated EF along the jet axis measured by using probe shows that the EF is maximum around 1.7 cm of the jet axis (which is the end of the transition phase) and is 23 kV/cm. The average EF
FIG. 9. Local Electric Field along the jet axis estimated by optical emission spectroscopy.

estimated by probe is much lower than the local EF measured by ratio method. The result found in
the probe method supports the calculated plasma jet electric field from the jet propagation modeling
result. The slowly decreasing average electric filed along the propagation phase also support the
decrees of the different species along the propagation phase of the plasma jet.

3. Electron Density Measurement

Consider that the electrons are moving with their drift velocity in the effect of local electric field. We
know that the drift velocity of the electron, \( v_d = \text{mobility} \times \text{electric field} \) and electron density, \( n_e = \text{current density} / (v_d \times e) \). The mobility of electron depends on the gas pressure, reduced electric
field, and the air mixture with the helium gas. The mobility of electron at different positions along
the jet axis for the different amount of air gas mixture with the helium is found from the Bolsig+
modeling and used to calculate the spatial evolution of the electron density. The spatial evolution of
the electron density for the electric field estimated from the electrical measurement (starts at 0.85 cm
of the jet axis) and the OES (starts at the reference point of the jet axis) is shown in Table I. It shows
that the electron density is almost oscillatory along the propagation phase and it increases at the end
of the propagation phase. The estimated average electron density is \( 2.4 \times 10^{11} /\text{cm}^3 \) and \( 6.3 \times 10^{11} /\text{cm}^3 \) from OES and probe diagnostic method, respectively and the maximum electron density at the
end of the propagation phase reaches to \( 1.2 \times 10^{12} /\text{cm}^3 \). The order of the electron density measured
in this paper is same as in Refs. 11. Average drift velocity is in the order of \( 10^7 \text{ cm/s} \) measured in
both methods justifies the experimental results. Along the propagation phase the electron density is
not constant, oscillatory. These results are also comparable with the jet propagation simulation by
Naidi\(^{42,43}\) and numerical simulation of the positive streamer propagation in air by Kulikovsky.\(^{46}\)
IV. DISCUSSION

The effect of different operating parameters on the plasma jet propagation has been studied and it has been found that on the propagation of the plasma jet, the applied voltage plays the most important role. Depending on the magnitude of the applied voltage pulse and its duration, the length and the propagation velocity of the plasma jet/bullet change. The correlation between the plasma jet length and the pulse duration confirms that the plasma jet is not isolated from the source voltage even when it comes out in the open air from the plasma pencil.

The transition from the non-stationary regime (transition phase) to the stationary regime (propagation phase) in streamer breakdown has been observed in Wagner’s work. For a fixed pressure and sufficiently high EF, the transition has been observed at a certain point of the plasma jet. In our case this transition took place within \( z = 1.0 \text{ cm} \) to \( z = 1.75 \text{ cm} \) of the jet axis. In this region the acceleration of the plasma bullet greatly increases and it depends on the input voltage and the plasma chemistry. Plasma jet velocity increases linearly with applied voltage. It is well established that in streamer breakdown the plasma velocity increases for higher electric field and at lower electric field this velocity goes down and it decreases with the length of the plasma channel.

Spatially resolved emission spectrum of the plasma jet shows that, in the plasma bullet’s propagation, the input energy and gas mixture plays an important role. The intensity of different species increases with applied voltage and it is almost the same for different pulse widths. The variation in the gas mixture along the jet axis changes the intensity curve of the different species. The point where the air mixing with helium is higher, the emission from nitrogen, oxygen, and helium shows a prominent change. Until the end of the transition phase the intensity ratio curve of the nitrogen bands along the jet axis is same in shape as the plasma bullet velocity curve. Along the propagation phase of the plasma bullet, the \( \text{N}_2 \) \((\text{C})\) state plays an important role. This low energy \( \text{C} \) state can be excited by energetic electron or by long lived metastable. The stepwise excitation is...
TABLE I. Electron density and Electron drift velocity along jet axis from the beginning measured by two different methods

<table>
<thead>
<tr>
<th>Drift Velocity (10^7 cm/s)</th>
<th>Electron Density (10^11 cm^-3)</th>
<th>Drift Velocity (10^7 cm/s)</th>
<th>Electron Density (10^11 cm^-3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.53</td>
<td>4.80</td>
<td>3.53</td>
<td>3.29</td>
</tr>
<tr>
<td>3.60</td>
<td>3.23</td>
<td>5.55</td>
<td>1.46</td>
</tr>
<tr>
<td>4.83</td>
<td>2.33</td>
<td>1.24</td>
<td>5.50</td>
</tr>
<tr>
<td>5.72</td>
<td>1.68</td>
<td>0.77</td>
<td>9.18</td>
</tr>
<tr>
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<td>6.46</td>
<td>1.26</td>
<td>0.12</td>
<td>7.06</td>
</tr>
<tr>
<td>5.88</td>
<td>1.16</td>
<td>0.95</td>
<td>8.46</td>
</tr>
<tr>
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<td>1.35</td>
<td>0.89</td>
<td>1.23</td>
</tr>
<tr>
<td>4.19</td>
<td>1.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.58</td>
<td>2.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.55</td>
<td>3.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.55</td>
<td>4.32</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FIG. 11. Average Electric Field of the plasma jet along the jet axis estimated by dielectric probe measurement.

also possible along the propagation phase, which is not considered in our observation. The local EF along the plasma jet axis shows that the height EF is at 1.2 cm of the jet axis and it is 95 kV/cm; this is same as the EF calculated for positive streamer propagating in air.45,46 At the end of the transition phase, the estimated electric field measured by dielectric probe is 24 kV/cm. Along the propagation phase the EF measured by probe is lower than the EF calculated from line ratio. The local EF and the average EF of the plasma jet reveal that the jet EF is enough for the streamer break down process.

The calculated drift velocity from the jet current density and the estimated EF is in the same order (10^7 cm/s) as the jet front velocity measured from the image of the plasma jet. The electron
density shows a spatial oscillation along the propagation phase. Morrow,48 and Wu and Kunhardt49 also observed a spatial oscillation of the electron density profile in streamer propagation in SF6 and the mixture of N2 - SF6 gas, respectively. The streamer breakdown model done by Lozanskii50 shows that at the end of the streamer, the curvature of the streamer front become sharp, and the electric field increases at the tip, which increases the electron density and the streamer front velocity.

The established relation between the pulse width, jet length and the average jet velocity says that the jet propagation is similar to the ionization wave propagation, but in ionization wave propagation the streamer breakdown process plays the significant role. It has three distinct propagation phases as streamer and the local electric field, electron density and the propagation velocity is similar to the streamer breakdown process in air. Similar investigation need to be conducted for longer pulse width to understand the propagation of the plasma jet more clearly.


