Atmospheric pressure plasma jet in controlled atmosphere: electric fields and propagation dynamics

To cite this article: Serajoddin Razavizadeh et al 2018 Plasma Sources Sci. Technol. 27 075016

View the article online for updates and enhancements.
Atmospheric pressure plasma jet in controlled atmosphere: electric fields and propagation dynamics

Serajoddin Razavizadeh\textsuperscript{1,2}, Hamid Ghomi\textsuperscript{1} and Ana Sobota\textsuperscript{2}

\textsuperscript{1} Laser and Plasma Research Institute, Shahid Beheshti University, Tehran, Iran
\textsuperscript{2} Department of Applied Physics, EPG, Eindhoven University of Technology, The Netherlands

E-mail: s_razavizadeh@sbu.ac.ir

Received 22 February 2018, revised 26 May 2018
Accepted for publication 19 June 2018
Published 13 July 2018

Abstract

We investigate the influence of the surrounding gas on the behaviour of guided ionization waves by measuring the electric field, propagation dynamics and emission spectra of a kHz operated helium plasma jet in surrounding gases such as nitrogen, oxygen and dry air. The electric field measurements performed using an electro-optic BSO crystal and the amount of deposited charge on the dielectric surface were calculated. These measurements showed a unique growth profile of the surface discharge in each of these surrounding gases after the guided ionization waves reaches the dielectric surface. The branching of surface discharges is observed when the nitrogen was used as the surrounding gas. The surface discharge profile in dry air and oxygen was diffused without any branching and it is wider in oxygen. The speed of growth of the discharge on the surface also decreases in nitrogen compared to dry air and oxygen. The measurements of propagation dynamics showed that the velocity of guided ionization waves is higher in oxygen containing gases. The result of this study showed that the presence of oxygen in the surrounding gas has a significant effect on guided ionization waves. These effects are mainly due to the photoionization of oxygen in the surrounding gas and also the electron detachment from the anions formed from oxygen.

Keywords: guided ionization wave, plasma bullet, photoionization, surrounding gas, electric field, atmospheric plasma jet

1. Introduction

In recent years the atmospheric pressure plasma jets have been studied by many groups for their potentials in biomedical applications and surface treatments \cite{1–6}. A lot of these studies have focused on the propagation mechanisms and physical and chemical processes of the guided ionization waves or so called plasma bullets after the observation of these waves \cite{7–10}. Most of the research was done in ambient air and because of the complicated chemistry of the air there is still a lot of unsolved questions about the role and influence of each chemical species on the propagation mechanisms of guided ionization waves \cite{10–15}. The guided ionization waves can also be generated in surrounding gases other than ambient air. The surrounding gas can influence the propagation mechanisms of guided ionization waves and it has been investigated by many groups \cite{16–20}.

Some experimental works used shielding gases around the helium flow channel \cite{16,17} and others put the plasma jet in chambers containing different background gases other than air \cite{18–20}. Xian et al \cite{16} reported that with increasing the oxygen in the surrounding gas the seed electrons will decrease and therefore the jet’s length decreases too. Schmidt-Bleker et al \cite{17} investigated experimentally and theoretically the role of electronegativity of the shielding gas by using the mixtures of $N_2/O_2$ and showed that the electronegative ions can promote the propagation of negative guided streamers. Akman et al \cite{20} showed that the surrounding gas of a helium jet forms a boundary layer which is necessary for the plasma bullets to propagate. They mentioned that the nitrogen and oxygen molecules are needed in this boundary layer to sustain
the ionization wave in the helium channel. The effect of mixing the surrounding gas with helium in the boundary layer was also investigated in the simulations of Naidis [21].

The photoionization process is another important effect which is related to the density of nitrogen and oxygen molecules in the surrounding gas. There are many experimental studies which explain the role of photoionization on propagation of positive streamers [22–26]. Nijdam et al [26] investigated the role of photoionization in propagation of positive streamers in different N2/O2 mixtures.

The role of photoionization in propagation of the guided ionization waves was investigated in simulations of Breden et al [27] and Naidis [21]. Breden et al [27] simulated the propagation of a guided streamer in a helium jet in ambient air with and without the photoionization effect and showed that the photoionization process can enhance the velocity of guided streamers.

In this research, a kHz atmospheric pressure helium plasma jet is used as a source for producing the guided ionization waves in different surrounding gases like nitrogen, oxygen and dry air. We studied the impingement of the helium plasma jet on a dielectric surface in different surrounding gases. This paper provides spatially and time-resolved measurements of the electric field on a dielectric surface in controlled atmosphere. We also measured the propagation dynamics and optical emission spectra to get more insights into the effect of surrounding gases. The roles of chemical species, photoionization process and the impurities are discussed in detail.

2. Experimental setup

A 30 kHz AC plasma jet was used in the experiments, described in detail in [13, 28–30]. The powered electrode was a stainless steel pipe with an inner diameter of 0.8 mm at 2 kV voltage amplitude. The powered electrode was placed in the center of a Pyrex capillary with inner diameter of 2.5 mm and outer diameter of 4 mm. Helium was flown through the powered electrode. The grounded electrode was a copper ring with 2 mm thickness which is placed at 5 mm away from the powered electrode outside of the capillary, see figure 1.

To put the helium plasma jet in different surrounding gases other than ambient air, we used a stainless steel cylindrical vessel with inside volume of 1.8 liter. All experiments were done at atmospheric pressure.

In the beginning of each experiment, we flushed the vessel with a desired gas at a flow rate of 2000 sccm for about 20 min. The purity of nitrogen was 99.9% and oxygen was 99.999%. After that, the helium was flown through the capillary of the jet for another 10 min at a constant rate from 700 to 1000 sccm, meanwhile the surrounding gas flow remained the same. The purity of helium was 99.999% and we used a fully stainless steel gas line for helium feed. This procedure will provide a homogeneous mixtures of helium (up to 33%) and the surrounding gas in the vessel. After 30 min of flowing the ambient gas, we started the jet.

For the electric field measurements, the plasma jet was implemented horizontally on one side of the vessel at 45° with respect to the symmetrical axis of the vessel. The surrounding gas came through the vessel from the bottom and exited through a long exhaust tube on the top, to flush the other gases in the vessel and making sure to have a continuous flow rate of desired gases in the vessel. We measured the electric field for helium flows of 700 to 1000 sccm while the surrounding gas flow was 2000 sccm. The electric field was measured using the Pockels effect when the plasma jet impinged on an electro optic BSO crystal in a surrounding gas other than the ambient air. The electric field measurement of guided ionization waves using a BSO crystal is fully described in [28, 29]. The Senarmont setup was used for measuring the changes in refractive index of the BSO crystal [31] and it is shown in figure 2. The BSO crystal was placed in the center of the vessel at 7 mm away from the end of the jet’s capillary.

As described in previous publications [28, 29] a 4Quik E iCCD camera was used as a detector for the electric field measurements. The electric field throughout the thickness of the crystal can be calculated as follows:

$$E = \frac{\lambda}{\pi d n_0^3} \frac{I - I_0}{r_{\text{max}} - r_{\text{min}}}$$

where $\lambda = 633$ nm is the wavelength of the LED, $d = 0.5$ mm is the crystal’s thickness, $n_0 = 2.54$ is the index of refraction of the BSO and $r = 4.8$ pm V$^{-1}$ is the Pockels coefficient. $I_0$ and $I$ are the measured light intensities without and with the applied electric field, respectively. The intensities of $I_{\text{min}}$ and $I_{\text{max}}$ are the minimum and maximum possible intensities for this optical system.

The iCCD exposure time was 100 ns and the integration time was 2800 $\mu$s which means each measurement is the overall effect of almost 85 bullets. The camera was triggered on the voltage pulse from the source, the voltage-current characteristics of the power source described in [28]. This short exposure time allows us to study the new emerged surface discharges which [29] called tail in the early times after the impact of guided ionization wave with the BSO’s surface. The moment of impact can be altered by the type of surrounding gas and the helium flow rate. We will take the time of impact ($t_i = 0$) in each experiment as the reference time for comparing the results of electric field measurements.

For measuring the propagation dynamics of guided ionization waves and the spectroscopic measurements, we used another vessel which the plasma jet was installed vertically at the top and operating downwards. The second vessel
was made of glass with two quartz windows on both side. The surrounding gas entrance, exhaust and other parameters was the same as the experiments for electric field measurements. The dynamical parameters such as the velocity, diameter of ionization waves and jet’s length was measured with the iCCD camera. The exposure time of the iCCD was 10 ns and we took pictures at time steps of 100 ns after the guided ionization wave passes the grounded electrode of the jet.

The emission spectra of the Helium plasma jet in different gases was taken with an AVANTES spectrometer (AvaSpec2048TEC).

3. Results and comparison with published work

3.1. Electric field and surface charge

As described in previous publications [28, 29], we measured the averaged electric field values throughout the thickness of the crystal (0.5 mm) from the moment of impact of ionization wave with the crystal’s surface. The electric field measurements were done time resolved in time steps of 100 ns.

The initial profile of the surface discharge is the point in which the guided ionization waves reaches the surface of the crystal and we call it contact spot. After the impact of guided ionization wave, a newly formed surface discharge will appear on the surface which we called the tail [29]. This elongated surface discharges will appear for helium flows of 800 sccm and higher. According to [29] a minimum amount of deposited charge in the contact spot is needed for elongation of the discharge, which is provided for the helium flows of 800 sccm and higher. Figure 3 shows the averaged electric field in the BSO crystal for a helium flow of 900 sccm in three different surrounding gases: dry air, nitrogen and oxygen. The gas flow direction was shown in figure 3(d) and it is the same for all the measurements.

These electric field values are negative because the orientation of the electric field is opposite to the propagation direction of the incident light. The first figure in each row shows the electric field of the contact spot. It can be seen that the diameter of contact spot increases with increasing the concentration of oxygen at the surrounding gas. Also the place of the contact spot is not the same in different surrounding gases.

In addition, (i) the elongated pattern for the surface discharges (tail) is not the same in different gases; (ii) the speed of growth of the discharge on the surface is lower when the nitrogen is the surrounding gas.

Figure 4 shows the average electric field at $t_l = 2$ s in dry air, nitrogen and oxygen. The difference in discharge patterns are clearly visible when there is a fully grown surface discharge. The surface discharge pattern for the dry air is the same as the ambient air [28, 29]. The tail discharge reaches from 0.5 mm to almost 2 mm with increasing the helium flow from 800 sccm to 1000 sccm.

The discharge profile in oxygen is elliptical and it is wider than in dry air. It is extended around the contact spot but mostly elongated in the direction of the helium flow on the surface. Also the tail moves backwards about 0.3 mm. The discharge area increases with increasing the helium flow and it reaches up to 3.1 mm$^2$ for helium flow of 1000 sccm.

The discharge profile in nitrogen surrounding gas shows branching on the surface and forms multiple new discharge channels. These new branches remain stable during the measurements and they do not change during the subsequent voltage cycles.

The speed of growth of the discharge on the surface is higher in oxygen containing gases. As it can be seen from figure 3, it will take more than $1 \pm 0.1$ $\mu$s to have a full grown surface discharge in nitrogen, but this growth time is almost $0.5 \pm 0.1$ $\mu$s for the dry air and oxygen. Our electric field measurements for helium flows of 800 and 1000 sccm also shows the slow growth of the surface discharges in nitrogen.

The uniform field approximation can be used to obtain the surface charge from the electric field values on the surface [29]. This approximation is only valid when the electric field can be assumed uniform throughout the crystal. The thickness of our crystal (0.5 mm) is comparable to the area of spreading the charge (3.1 mm$^2$ at most) on the surface and we only have the averaged values in the BSO crystal, so we have to use the corrections in [29] to obtain the real values of electric field.
and the amount of charge on the surface. A lookup table [29] is used to calculate the electric field values on the surface from the average values.

The maximum value of measured electric field is in the contact spot for all the surrounding gases. Figure 5 shows the maximum values of electric field as a function of helium flow, averaged through the thickness of the crystal and at the surface. All the error bars represent the standard deviation of uncertainty which is calculated from a set of repeated measurements. The type of surrounding gas does not seem to have a significant effect on the maximum value of electric field. The average values of electric field and the compensated values on the surface are measured between 3–6 kV and 6–9 kV, respectively. These values are lower than those reported in [21, 32, 33], this is due to the nature of our measurements method because the electric field is induced in the target due to charge deposited on the surface instead of being measured directly within the plasma plume [28, 29]. Consequently, the electric field caused by the volume charge in the discharge away from the surface of the target is not measured. These values are an excellent indicator of the electric field felt at the surface of any comparable dielectric target, useful for applications where the plasma interacts with dielectrics.

The amount of deposited charge on the surface is calculated using the same procedure for a fully grown discharge pattern. Figure 6 shows the total deposited charge on the surface as a function of helium flow at different surrounding gases. The amount of deposited charges increases for all the surrounding gases with increasing the helium flow. The influence of helium flow on the surface discharge in different gases is the same as ambient air and it has its origin in the gas mixing on the surface [28, 29]. The amount of charges in the moment of impact for all the surrounding gases are in the same range, between 150 ± 30 pC to 250 ± 50 pC. But after

**Figure 3.** The averaged electric field (kV/cm) in the BSO crystal for helium flow of 900 sccm in different time steps after the impact of guided ionization wave \((t_i = 0)\). The voltage amplitude is 2 kV and it is averaged for 85 exposures of 100 ns. The surrounding gas is dry air for (a)–(d), nitrogen for (e)–(h) and oxygen for (i)–(l).
the growth of the discharge on the surface, the total surface charges in oxygen and nitrogen surrounding gases is higher than in dry air. This is due to wider profile of the surface discharges in pure gases of oxygen and nitrogen compared to dry air. The magnitude of the electric field and the amount of deposited charge on the surface in dry air are similar to those in [28] and [29] which is done in the same condition in ambient air. The results in [28] and [29] show up to 20% less electric field and surface charge. There are two possible causes for this. One, the ambient air in [28, 29] was humid. Two, the gas mixture in the vessel in this work contained 30% of He, making Penning reactions between He and nitrogen. The maximum amount of deposited charge could reach up to 1200 ± 180 pC in nitrogen surrounding gas for helium flow of 1000 sccm. The average surface charge density is about 28 nC/cm² in ambient dry air, 30 nC/cm² in ambient oxygen and 32 nC/cm² in ambient nitrogen. We assumed a sphere shape for the guided ionization wave and found that the average charge density is \(3.5 \times 10^{18} \text{ cm}^{-3}\). This is consistent with [14, 34].

### 3.2. Propagation dynamics in the gas phase

The guided ionization waves travel 12 mm inside of the capillary after the ground electrode and then exit into the surrounding gas. Figure 7 shows the velocity of guided ionization waves inside of the jet’s capillary for different surrounding gases. It can be seen that there is no significant difference between the velocities for helium flows higher than 700 sccm, but the diffusion of surrounding gas into the capillary is higher in helium flow of 700 sccm and it can slightly influence the propagation of guided ionization waves. For helium flow of 700 sccm, the average velocity of guided ionization waves inside the capillary is lower when the nitrogen is the surrounding gas (about 9 km s\(^{-1}\)) and they have the highest average velocity (about 12.2 km s\(^{-1}\)) in oxygen surrounding gas. With increasing the helium flow the velocities inside of the capillary became independent of the type of surrounding gas.

The measurements of the velocity outside of the jets capillary clearly shows the influence of the surrounding gas. Figure 8 shows the velocity of guided ionization waves.
outside of the jet’s capillary for different surrounding gases. The guided ionization wave has the lowest velocity in nitrogen surrounding gas and the velocity in dry air and oxygen are almost the same. The average velocity in nitrogen surrounding gas for helium flows of 700 sccm, 800 sccm and 900 sccm is $6.1 \text{ km s}^{-1}$, $5.8 \text{ km s}^{-1}$ and $7.4 \text{ km s}^{-1}$, respectively, and for oxygen is $9 \text{ km s}^{-1}$, $11 \text{ km s}^{-1}$ and $10.3 \text{ km s}^{-1}$, respectively. It is clear that the higher concentration of oxygen molecules in the surrounding gas can increase the velocity of guided ionization waves.

The velocity curve of the guided ionization waves shows three distinct phases: (i) transition phase, (ii) propagation phase, and (iii) collapse of the guided ionization wave. These
Three phases were shown in Figure 8 and were described more comprehensively in [35]. The velocity of guided ionization waves increases along the transition phase to reach an almost stationary velocity in the propagation phase.

Figure 8 shows that the length of the transition phase is longer in oxygen containing gases which causes the higher velocities in these gases. On the other hand, the length of the propagation phase is always shorter in oxygen surrounding gas compared to nitrogen and dry air and the guided ionization waves start to collapse faster in oxygen. In helium flow of 900 sccm the length of the propagation phase for dry air, nitrogen and oxygen is 6.5 mm, 6 mm and 3.5 mm, respectively. The total length of the plasma jet (the maximum length which a guided ionization wave can travel outside of the capillary) is directly related to the length of the propagation phase [35].

Figure 9 shows the jet’s length in different surrounding gases. The jet has its maximum length in dry air and minimum length in oxygen, but for helium flows of 900 and 1000 sccm, the jet’s length also increases more in nitrogen surrounding gas. The maximum length reaches to 12 mm for helium flow of 1000 sccm in nitrogen.

The diameter of guided ionization waves decreases as they leave the capillary in all the surrounding gases and it is similar to ambient air [36, 37]. Figure 10 shows the average diameters of guided ionization waves in different surrounding gases. The average diameter is between 0.5 mm to 0.65 mm for different helium flows and their dependency on the type of surrounding gas is negligible.

3.3. Spectroscopic measurements

Optical emission spectroscopy was used to gain more insights into the species and impurities in our measurements. Figure 11 shows the optical emission spectra of the helium plasma jet in 3 different gases: dry air, nitrogen, oxygen. This spectrum consists of the following atomic lines or molecular bands: atomic oxygen at 777 and 845 nm, He lines at 706, 667, 587 and 471 nm, Hα line at 656 nm, N2⁺ lines at 427 and 391 nm, N2 lines at 380, 357, 337 and 315 nm and OH radical line at 309 nm. In all the spectra there is OH radical line which is due to the dissociation of H2O and shows the presence of water in our vessel.
In order to get more insight from these spectra, we compare them two by two. Figure 11(a) shows the emission spectra of helium jet in N₂ and O₂ gases. From this spectrum we can clearly see that there is some nitrogen left in the vessel in oxygen surrounding gas and there is also oxygen in nitrogen surrounding gas. Impurities are there because we didn’t pump down the system when changing ambient gases. In nitrogen spectrum, the wavelength range of 315 to 385 nm is dominated by second positive system of N₂ and the range from 391 to 428 nm by the first negative system of N₂⁺. In He-N₂ discharges, the N₂⁺ emission lines are often prominent due to Penning ionization of N₂ by helium metastable atoms [38, 39]. Even with trace amounts of N₂ in the vessel, the two N₂ systems will be intense.

Another notable lines in nitrogen compared to oxygen surrounding gas is the higher OH and H lines and even higher helium emission lines in nitrogen. The production of these species is mostly due to energetic electron impact [40, 41] and because the oxygen is electronegative and reduces the electron density [42, 43]. Higher emission lines of these species in nitrogen are expected compared to oxygen surrounding gas. OH radicals and H atoms can also be produced by Penning ionization of water molecules by helium metastables [41].

The helium line 706 nm is corresponding to a transition from the upper level 1s3s(3S) to the lower level 1s2p(3P⁰), the energy of the upper level is almost 22.7 eV [44] which is provided by high energy electrons in plasma. This line will decrease by increasing the oxygen concentration.

Figure 11(b) shows the emission spectra of helium plasma jet in nitrogen and dry air. The emission lines in dry air and nitrogen is very similar but there are some differences like the more intense lines of N₂ and N₂⁺. The helium emission line of 706 nm is higher in dry air compared to nitrogen. According to [45], the decrease in He metastable is not due to the presence of more N₂ but is due to the absence of O₂ in the surrounding gas.

4. Discussion

Two important results in this study should be noted. The first one is the lower velocity of guided ionization waves in nitrogen and the slow growth of discharges on the dielectric surface in nitrogen surrounding gas. Also, the velocities of guided ionization waves in dry air and oxygen are almost the same. The second result is the different profile of the grown surface discharges in different gases. The surface discharge in nitrogen gas forms new discharge channels (branches). From figure 4, we can see that the growth of surface discharges in oxygen and dry air are more similar. The surface discharge is uniformly wider in oxygen surrounding gas compared to dry air but it doesn’t form any branches. The similarities and the differences between these results, suggests that the presence of oxygen molecules in the surrounding gas of a helium plasma jet has a significant effect on the propagation of the guided ionization waves. To explain these results, we
compare them with the results of other experiments on streamer discharges and plasma jets in different gases.

4.1. Faster surface discharges and guided ionization waves in oxygen containing gases

The role of oxygen in the surrounding gas can be explained by both its electronegativity and photoionization. The guided ionization waves, which we studied in this research, are similar to positive streamers [10]. The photoionization plays an important role in the propagation of the positive streamers in oxygen containing gases. The UV radiation which is emitted from the excited molecular nitrogen, with higher energy levels than the ionization of oxygen, can ionize the molecular oxygen. Yi and Williams have shown that the positive streamers will propagate faster in higher oxygen concentrations due to the photoionization of oxygen [22]. Ono and Oda also reported the similar results when they increase the oxygen concentration in their experiment [23].

The role of photoionization in the propagation of guided streamers was investigated theoretically by Breden et al [27]. They considered a photoionization model in air for their simulation and showed that the guided streamers are much slower when there is no photoionization in the system. According to [17], the photoionization itself is not the only reason for promoting the guided ionization waves. The low energy electrons produced by photoionization or diffused from the plasma plume can quickly consumed to form \( \text{O}_2 \) by 3-body attachment or \( \text{O}^- \) by dissociative attachment. These anions can provide seed electrons through the electron detachments process in the subsequent positive half-cycle.

We propose that the increased speed of the guided ionization waves in dry air and oxygen is caused mainly by electron detachment and somewhat by photoionization. A follow-up numerical study is suggested for a comparison between these two effects. The faster growth of surface discharges in oxygen and dry air compared to nitrogen can also be explained by the increased photoionization of oxygen in the gas mixing on the surface.

The guided ionization waves are faster in pure oxygen surrounding gas but their travelling length and the length of the propagation phase is shorter. This is mainly due to the electronegative property of oxygen and more attachment of electrons to the oxygen molecules in the dark channel in negative half cycle of AC voltage when there is no ionization wave presents [16]. Our spectroscopic measurements also showed the reduction in helium emission lines in oxygen surrounding gas which is probably due to electron attachment to oxygen.

4.2. Branching in surface discharges in nitrogen

Briels et al showed that at low oxygen concentration, streamers branch more [24, 25]. Nijdam et al presented the same results and they explained how the lower photoionization rate of oxygen is related to the branches and feather structures in streamers in oxygen-nitrogen mixtures [26]. According to their interpretation, branches are actually avalanches which are moving towards the streamer head and these avalanches can be affected by the absorption length of photon which is dependent on the oxygen concentration. Like them, we can consider two extreme cases, one with low oxygen concentration in front of the surface discharge contact spot and another with high oxygen concentration.

In the first case, with low oxygen concentration, the photoionization rate is low and it will happen far from the surface discharge contact spot. The free electrons, which are created by the photoionization process, cannot form avalanches immediately because the electric field is not strong enough. Only a few electrons in random places might be close enough to the contact spot where the electric field is highest and they form avalanches in random directions. These separate avalanches are visible in the form of the branches in figures 3 and 4. The surface discharges that we have in nitrogen cannot extend uniformly because of low oxygen concentration in the gas mixing on the dielectric surface. The stability of these branches in the subsequent voltage cycles is probably due to residual charge which remains from previous discharges on the surface and lowers the breakdown threshold. This explanation is very similar to the idea of memory effect in the plasma jet [36, 46].

In the second case, there is a sufficiently high oxygen concentration in the surrounding gas. There will be enough UV radiation and the photoionization rate will be high, even near the contact spot. The electrons that are created will immediately be accelerated towards the contact spot and create avalanches. Because density of the seed electrons is much higher in front of the contact spot these avalanches will overlap and become part of the growing surface discharge. Therefore, the surface discharges will appear diffuse and they will not form visible branches [26].

5. Conclusions

In this work we investigated the propagation of guided ionization waves in oxygen, nitrogen and dry air. The electric field on a surface of a BSO crystal, propagation dynamics and emission spectra were measured to characterize the influence of surrounding gas on propagation of guided ionization waves. The comparison of the results showed that the presence of oxygen atoms in the surrounding gas has a significant effect on the propagation of the guided ionization waves.

The electric field measurements showed a unique profile of surface discharge for each type of the surrounding gas. For nitrogen as a surrounding gas, the surface discharge was branching and growing more slowly on the dielectric surface compared to oxygen containing gases. These branches are stable during the experiment and they do not change during subsequent voltage cycles.

The growth of surface discharges in oxygen and dry air are more similar and they grew faster on the crystal’s surface. The surface discharge is larger in oxygen surrounding gas compared to dry air. It is likely that the uniform
photoionization of oxygen at the surface causes the more extended and wider surface discharges in oxygen containing gases. The electric field at the crystal’s surface is independent of the type of surrounding gas but the total surface charge is higher in pure gases (O2 and N2) and reaches up to 1200 ± 100 pC for nitrogen with a helium flow of 1000 sccm.

Our measurements for the propagation dynamics showed that the type of surrounding gas can change the velocity and travelling distance of guided ionization waves. The velocity of guided ionization waves is always higher in oxygen containing gases and this is consistent with the results of electric field measurements which shows the faster growth of surface discharges in these gases. The proposed mechanisms to explain the higher speed of ionization waves in dry air and oxygen are electron detachment and photoionization. The jet has its maximum length in dry air and minimum length in oxygen. Also in nitrogen as a surrounding gas, the jet’s length will increase up to 12 mm for the helium flow of 1000 sccm. The electronegative property of oxygen can also decrease the density of seed electrons and it can decrease the propagation length of guided ionization waves.

The comparison of emission spectra in dry air and nitrogen suggests that the penning ionization between the helium metastable atoms and N2 is an important process for producing the N2+ ions.

Acknowledgments

S R acknowledges support from the Ministry of Science, Research and Technology of Iran, and Eindhoven University of Technology for its hospitality.

ORCID iDs

Serajoddin Razavizadeh @ https://orcid.org/0000-0001-8346-2056
Ana Sobota @ https://orcid.org/0000-0003-1036-4513

References

[8] Lu X and Laroussi M 2006 Dynamics of an atmospheric pressure plasma plume generated by submicrosecond voltage pulses J. Appl. Phys. 100 063302
[13] Sobota A, Guaitella O and Rousseau A 2014 The influence of the geometry and electrical characteristics on the formation of the atmospheric pressure plasma jet Plasma Sources Science and Technology 23 025016
streamers in air and nitrogen of varying density: experiments
on similarity laws J. Phys. D: Appl. Phys. 41 234008
[26] Nijdam S, Van De Wetering F M, Blanc R,
Van Veldhuizen E M and Ebert U 2010 Probing photo-
ionization: experiments on positive streamers in pure gases
and mixtures J. Phys. D: Appl. Phys. 43 145204
[27] Breden D, Miki K and Raja L L 2012 Self-consistent two-
dimensional modeling of cold atmospheric-pressure plasma
jets/bullets Plasma Sources Science and Technology 21 034011
[28] Slikboer E, Guaitella O and Sobota A 2016 Time-resolved
electric field measurements during and after the initialization
of a kHz plasma jet from streamers to guided streamers
Plasma Sources Science and Technology 25 03LT04
[29] Slikboer E, Garcia-Caurel E, Guaitella O and Sobota A 2017
Charge transfer to a dielectric target by guided ionization
waves using electric field measurements Plasma Sources
Science and Technology 26 035002
helium atmospheric pressure plasma jet on a dielectric
Measurement of the electro-optic coefficients: description
and comparison of the experimental techniques Appl. Phys.
B 70 317–34
[32] Sretenović G B, Krstić I B, Kovačević V V,
Obradović B M and Kuraica M M 2011 Spectroscopic
measurement of electric field in atmospheric-pressure
plasma jet operating in bullet mode Appl. Phys. Lett. 99
161502
[33] Olszewski P, Wagenaaers E, McKay K, Bradley J W and
Walsh J L 2014 Measurement and control of the streamer
head electric field in an atmospheric-pressure dielectric
barrier plasma jet Plasma Sources Science and Technology
23 015010
[34] Breden D, Miki K and Raja L L 2011 Computational study of
cold atmospheric nanosecond pulsed helium plasma jet in air
Appl. Phys. Lett. 99 111501
pressure He-air plasma jet: breakdown process and
propagation phenomenon AIP Adv. 3 062117
between and control of guided and branching streamers in
DC nanosecond pulsed excited plasma jets IEEE Trans.
 Plasma Sci. 40 2888–99
[37] Jarrige J, Laroussi M and Karakas E 2010 Formation and
dynamics of plasma bullets in a non-thermal plasma jet:
influence of the high-voltage parameters on the plume
characteristics Plasma Sources Science and Technology 19
065005
[38] Poenarui V, Wertheimer M R and Bartnikas R 2006
Spectroscopic diagnostics of atmospheric pressure helium
dielectric barrier discharges in divergent fields Plasma
Processes and Polymers 3 17–29
[39] Ricard A, Décomps P and Massines F 1999 Kinetics of
radiative species in helium pulsed discharge at atmospheric
pressure Surf. Coat. Technol. 112 1–4
[40] Liu D X, Bruggeman P, Iza F, Rong M Z and Kong M G 2010
Global model of low-temperature atmospheric-pressure
He + H2O plasmas Plasma Sources Science and
Technology 19 025018
[41] Liu J J and Kong M G 2011 Sub-60 C atmospheric helium-
water plasma jets: modes, electron heating and downstream
reaction chemistry J. Phys. D: Appl. Phys. 44 345203
[42] Miller T M 2003 Electron affinities In CRC Handbook of
Chemistry and Physics ed D R Lide (Boca Raton: CRC
Press) pp 10–47
Nomoto Y and Adachi T 1997 Removal of NOx from flue
gas by corona discharge activated methane radical showers
J. Electrostat. 40 651–6
NIST Atomic Spectra Database (ver. 5.5.1)
Reuter S and Puech V 2015 The spatio-temporal distribution
of He (23S1) metastable atoms in a MHz-driven helium
plasma jet is influenced by the oxygen/nitrogen ratio of the
surrounding atmosphere Plasma Sources Science and
Technology 24 025015
[46] Li Q, Pu Y K, Lieberman M A and Economou D J 2011
Dynamic model of streamer coupling for the homogeneity of
glowlike dielectric barrier discharges at near-atmospheric
pressure Phys. Rev. E 83 046405