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Electric field measurement in the dielectric tube of helium atmospheric pressure plasma jet

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The results of the electric field measurements in the capillary of the helium plasma jet are presented in this article. Distributions of the electric field for the streamers are determined for different gas flow rates. It is found that electric field strength in front of the ionization wave decreases as it approaches to the exit of the tube. The values obtained under presented experimental conditions are in the range of 5–11 kV/cm. It was found that the increase in gas flow above 1500 SCCM could induce substantial changes in the discharge operation. This is reflected through the formation of the brighter discharge region and appearance of the electric field maxima. Furthermore, using the measured values of the electric field strength in the streamer head, it was possible to estimate electron densities in the streamer channel. Maximal density of $4 \times 10^{11}$ cm$^{-3}$ is obtained in the vicinity of the grounded ring electrode. Similar behaviors of the electron density distributions to the distributions of the electric field strength are found under the studied experimental conditions.

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I. INTRODUCTION

Non-thermal atmospheric pressure plasma jets occupy the attention of low temperature plasma (LTP) community for the last two decades, due to various physical phenomena interfering in its nature and its application in the field of medicine.1–4 Numerous theoretical and experimental studies revealed streamer properties of these discharges, and most of these researches are listed in several reviews.3,5,6 Low temperature plasma (LTP) jets are usually initiated by noble gas flow through inter-electrode space while electrodes are supplied by AC or pulse high voltage. The usual geometry of LTP jet is coaxial, with one powered, needle or ring, electrode and one grounded electrode around a dielectric tube usually dielectric barrier discharge; (2) discharge in the dielectric tube; and (3) discharge in the plume of the jet. Until this moment, most of the studies were focused on the guided ionization wave—plasma bullet investigation in the plume of the jet.7–11 Plasma bullets move along the predominant path, defined by the noble gas, usually helium or argon, mixing with ambient air. Plasma jet plume exists in the limits determined by exact maximal molar fraction of air in helium.12,13

The previous work of authors was also focused on the plume of the plasma jet. Ionization wave propagation and interaction with targets were investigated by means of fast imaging, electric field, and charge measurement using Stark polarization spectroscopy and Pockels effect.13–19 This article is devoted to discharge development in a dielectric capillary of the coaxial 30 kHz helium plasma jet with the emphasis on the electric field strength dependence on the gas flow rate. Discharge ignition and dynamics in dielectric tubes are also studied by several groups of authors.20–31 Ionization wave in dielectric tube travels in almost uniform gas mixture and in a well-defined space, but with the additional influence of dielectric tube on its propagation through the charge accumulation on the walls. Behind the ionization front, a conductive, quasi-neutral plasma column forms, while the positive charge deposits on the tube walls.27 The material of dielectric tube impacts the propagation properties of ionization waves. Higher permittivity increases the capacity of the tube walls and thus the charging time. As the consequence, peak velocity and peak electric field strength decrease with higher permittivity.26

II. EXPERIMENTAL SET-UP

Atmospheric pressure helium plasma jet of coaxial geometry described in the previous articles is also used in this study.13–16 It consists of Pyrex tube with inner diameter of 2.5 mm and outer diameter of 4 mm and two metallic electrodes. Powered electrode is stainless steel pipe with inner and outer diameters of 0.8 and 1.6 mm, respectively. It is centered inside the dielectric tube, while the grounded electrode, 3 mm wide ring, is placed around dielectric tube 5 mm downstream the powered electrode, see Figure 1. Helium flow (Messer, 99.996% purity) through metallic pipe is controlled by means of mass flow controller Bronkhorst® in the range of 700–2000 standard cubic centimeters per minute (SCCM). Metallic pipe is supplied by sinusoidal high voltage with amplitude of 2 kV and frequency of 30 kHz. Voltage is measured using Tektronix P6015A high voltage probe, and current is determined as a voltage drop over 100 Ω non-inductive resistor. For the spectroscopic measurement, Solar
MSDD 1000 spectrometer with the focal length of 1 mm and the grating of 1200 grooves/mm is used. The light emitted from the capillary tube is projected on the slit of spectrometer by achromatic lens with a focal length of 150 mm. Magnification ratio was 1:3. Due to the low intensity of the observed light, slit width was set to 70 μm, which resulted in the instrumental half width of 0.051 nm. The ICCD was triggered using a time-delayed pulse signal from a non-inductive resistor inserted between the grounded electrode and the grounding point.

The aim of this work was the measurement of the electric field strength along the capillary tube for different gas flows. Electric field strength was measured by Stark polarization spectroscopy method. More details about electric field measurement using this method in low pressure glow discharge, DBD, plasma jet, and radiofrequency atmospheric pressure discharge in helium can be found in our previous publications.17–19,32–39 The method is based on the measurements of the distance between two helium lines, forbidden and allowed, which are shifting depending on the value of the external electric field. In order to separate two polarized components of the emitted light, plastic polarizer was mounted in front of the slit, and only p-polarized light was recorded. In this work, we used the He (21P-41D) allowed line at 492.19 nm and the closest forbidden He (21P-41F) line.

Discharge under investigation emits one guided ionization wave during the positive half cycle.15 Therefore, electric field is measured for the positive current signal, i.e., during the propagation of the positive streamer. Gate width of typical 5 μs captured entire ionization wave propagation, from the inter-electrode space until the plume end. Streamer passes the length of the tube for about 2 μs, which corresponds to the average velocity of about 10 km/s. Ionization wave emits light only from the ionization front—streamer head. Consequently, spatially resolved measurement also reveals a temporal development of the streamer as it was argued by Sobota et al.,13 see Fig. 2(b) in this reference.

For example, in the mentioned article where the same discharge is investigated, spatio-temporally resolved electric field measurements were compared with the spatially resolved measurements. The overlap of the data initiated further integrated measurements in order to reduce the duration of time consuming measurements anyhow. The obtained electric field strength values are close to the maximal values of the electric field in the streamer head. Figure 2 shows the representative line profile emitted from the capillary. Spectrum consists of the forbidden and the allowed counterpart. Allowed line has a Lorentzian half width of 0.084 nm. This half width represents the influence of pressure broadening which consists of van der Waals and resonance broadening and corresponds to gas temperature of about 300 K at atmospheric pressure.18 This means that the observed line is not significantly broadened by the influence of the emission from the tail of the streamer, which is the case for higher electric fields in the plume, especially for the plasma jets supplied with fast rising high-voltage pulses.40 The observed helium line is weak and visible only in the regions with significant electric field strength.19 Electric filed along the whole capillary appears to be not so high, and consequently, the electric field behind the streamer head is lower and in this case insufficient to excite enough helium atoms to emit He 492.19 nm line in that region.

III. RESULTS AND DISCUSSION

A. Visualization of the discharge in the tube

Differences in the operation properties of plasma jet for different helium flows are visible by naked eye. Beside the length of the plume, the changes in the discharge in the tube with the increase in gas flow could be also observed, see Figure 3. While the intensity of the emission from the capillary for 700 SCCM almost homogeneously decreases along the tube, the intensity maxima in the second part of the capillary is observed for the flow of 2000 SCCM. One can conclude that the gas flow rate greatly influences the discharge appearance and that flows above a certain value cause a local maximum in the intensity of the emitted light between 10 and 15 mm away from the end of the charged electrode,
which is clearly demonstrated in the right part of Figure 3. Such an occurrence is further investigated by spectroscopic measurements of the electric field distribution in the glass tube for different gas flow rates.

B. Electric field strength distribution

The results of the electric filed measurements in the dielectric tube for different gas flows are presented in Figure 4. The result errors, estimated from the quality of the fit, are in the range of 7%–15%. For all gas flows, electric field has a maximum just after the grounded electrode and its value decreases monotonically along the tube in its first third. For lower gas flows, 700–1500 SCCM, electric field reaches a plateau, which at the end of the profile has a slight drop to the values of 5–7 kV/cm. Decrease in the electric field strength in the streamer head along the jet tube is also perceived in the electric field measurement experiments carried out in the plasma gun by Pockels-effect based electro-optic sensor (Kapteos company). Such a tendency could be found in a recently published study of the plasma bullet propagation in long dielectric tubes, where the influence of the tube diameter on the discharge appearance was investigated.

For higher gas flow rates, electric field strength first decreases, but instead of plateau, its value has another rise; it goes through second maximum and then decreases as the ionization wave approaches to the end of the capillary. Such a behavior is in consistence with the appearance of the discharge region with the bright core observed in Figure 3. Observing this phenomenon by the naked eye, one could see the constricted hairline plasma structure in this region, which is much brighter than the expanded surrounding. According to this, it is reasonable to conclude that this is a region with higher space charge density. It is difficult to determine the reason of such behavior, but it is clear that it is the consequence of the gas flow rate and the mutual influences between gas flow and discharge itself. The gas flows of 700, 1000, 1250, 1500, 1750, and 2000 SCCM correspond to the Reynolds numbers of 54, 78, 97, 116, 136, and 155, respectively, and according to these values, all flows are laminar. However, it was shown in our previous article that discharge onset induces vortices in the gas flow for higher gas flows. Satti and Agrawal investigated flow structure of helium gas jets into air for Reynolds numbers from 40 to 150. For low jet Reynolds numbers, the flow was steady and back flow of air upstream of the tube exit was recorded. At higher jet Reynolds numbers, 90 and 150, buoyancy induced acceleration contracted the jet core to form a toroidal vortex by entrainment of the ambient air. This caused self-excited periodic oscillations at a unique frequency at jet Reynolds numbers of 90 and 150. Furthermore, vortices interacted with helium jet core could also affect the laminarity of the flow inside the tube and be a main cause of the formation of observed region with the increased electric field.

Interestingly, the final electric field strengths at the exit of the capillary are all in the same range of 5–7 kV/cm. Accordingly, the electric field strength drops to about a half, from 10–11 kV/cm in the vicinity of the grounded electrode to 5–7 kV/cm at the tube exit. It was reported in our previous articles that the electric field in the plume of the jets starts to rise from the tube end along the jet axis, see also Figure 7. Moreover, electric field in the plume starts to rise from the same values (5–7 kV/cm) for all gas flows, which demonstrates the consistence between the results and the reproducibility of the used measurement method. The probable reasons for the decrease in the electric field strength along the tube could be charging of the inner dielectric walls inducing subsequent electric potential shielding.
C. Estimations of the electron density in the streamer channel

Directly obtained values of the electric field in the streamer head enable the estimation of the electron density in the streamer channel by equating the inverse of the Maxwell relaxation time to the ionization frequency at the maximum field in the streamer head \( \frac{1}{\tau_0} = n_e \nu_i \), where \( \nu_0 \) is the vacuum permittivity, \( e \) is the elementary charge, \( n_e \) is the electron density, and \( \nu_i \) is the ionization frequency.\(^1\) If we recall the meaning of the Townsend ionization coefficient \( \alpha = \frac{\nu_i}{\nu_0} = \frac{\nu_i}{\nu_0} N \), where \( \nu_i \) is the electron drift velocity and \( E \) is the electric field strength, we will obtain the formula \( n_e \approx \frac{\nu_i}{\nu_0} E \).\(^3\) Such an approach to the electron density estimation in the streamer channel, i.e., plasma, is not new. It was introduced by D’yakonov and Kachorovskii for streamers in semiconductors, and later used by Kulikovsky for streamers in air,\(^4\) by Boeuf \textit{et al.} for streamers in helium plasma jets,\(^1\) and lately by Babaeva and Naidis, also for streamers in air.\(^5\) More details about this topic could also be found in the book of Bazelyan and Raizer.\(^6\)

Ionization coefficient \( \alpha \) is also the function of the electric field, and it can be obtained from Bolsig.\(^7\) Figure 5 shows the dependence of the \( \alpha \) coefficient on the electric field strength for the range of the electric field of 4–18 kV/cm, i.e., the range of the measured values in the present experiment. Townsend coefficient is calculated for five gas compositions: pure He, He with the admixture of 100 ppm, 1000 ppm, 1% and 2% of air. In the last four cases, the \( \alpha \) coefficient represents the reduced Townsend coefficient. The admixture of 1000 ppm of air in He is estimated as the upper limit of the dielectric tube where constant flow of helium with initial 40 ppm of impurities is present. Higher air fractions are presented for the sake of comparison with the measurements made in plume.\(^1\) It is clear from the graphs in Figure 5 that the mentioned admixtures do not affect strongly the values of the ionization coefficient; thus, one could consider the discharge in the tube as the discharge in pure helium.

For the calculation of the electron density, it is appropriate to use the functional dependence of the Townsend ionization coefficient \( \alpha \) on the electric field strength. The usual generalized and simplified form deduced under several assumptions by Townsend\(^8,9\) has an exponential form \( \alpha = N e^{-\frac{E}{B N}} \), where \( N \) is the number density of gas molecules in cm\(^{-3}\) and \( E \) is the external electric field in kV/cm. Parameters \( A \) and \( B \) depend on the gas type and electric field range, and they are derived from the fit of data obtained from Bolsig.\(^7\) Sets of electron impact cross sections were taken from the Biagi database.\(^5\) Values are calculated for the atmospheric pressure and the gas temperature of 300 K. For the observed range of electric field, obtained parameters are as follows: \( AN = (700 \pm 10) \) cm\(^{-1}\) and \( BN = (26.0 \pm 0.3) \) kV/cm. Electron density calculated for the observed range of the electric fields using the expression \( n_e = \frac{\nu_i}{\nu_0} AN e^{-\frac{E}{BN}} \) is also presented in Figure 5. As it can be concluded from the previous expression, electron density in the streamer channel exponentially rises with the rise of the electric field in the streamer head. For the lower electric field, the value of 4 kV/cm electron density is about \( 4 \times 10^9 \) cm\(^{-3}\), while at 6 kV/cm, it has an order of magnitude higher value, and finally, for the maximal electric field in the capillary of about 12 kV/cm, electron density reaches the value of \( 5 \times 10^{11} \) cm\(^{-3}\). For the electric field strength in the streamer head of 18 kV/cm, electron density in the streamer channel exceeds \( 10^{12} \) cm\(^{-3}\).

Using the data for the electric field strength distribution shown in Figure 4 and the previous analysis, it was possible to estimate electron density distributions in the streamer channel for different gas flows. The results are presented in Figure 6.

Electron density has its maximum near the grounded electrode for all flows, similar to the electric field distribution. Correspondingly, concentration of the electrons decreases along the tube, but with the higher rate and the drop could be described by the exponential function. Electron density falls from \( 3–4 \times 10^{11} \) cm\(^{-3}\), near the ring electrode, to the values of \( 2–4 \times 10^{10} \) cm\(^{-3}\) at the exit of the capillary. The starting and the final values of the electron densities are mostly the same, but for the higher gas flows,
due to the increase in the electric field, electron densities attain the additional maxima. Electron densities estimated in this work may look underestimated, but they are in line with modeling results presented by Jansky et al. where the peak density of 10^{12}\,\text{cm}^{-3} is obtained for slightly different experimental and modeling conditions. The electron density in helium plasma jet is measured by Hübner et al. utilizing the Thomson scattering technique.\textsuperscript{51} Measurements are performed on a nanosecond pulsed high voltage dielectric barrier discharge helium plasma jet flowing into the ambient air surrounding. Results are presented for the effluent only. At the distance of 2\,mm from the nozzle, electron density at the axis of the jet is below the detection limit, while towards the rim it rises above detection limit reaching 3–4 \times 10^{12}\,\text{cm}^{-3}. The detection limits are mostly determined by the laser stray light and are in the order \( n_e > 10^{12}\,\text{cm}^{-3}. \textsuperscript{52}\) The electron densities estimated in this work are well below 10^{12}\,\text{cm}^{-3} just before the exit of the tube. In order to make better comparison with the measurements of the electron density by Thomson scattering and the estimation presented in this article, we calculated electron densities in the tube and the effluent of the plasma jet operating with gas flow of 1000 SCCM. Results are presented in Figure 7. Systematic measurements of the electric field in the effluent of the plasma jet are presented in our previous article.\textsuperscript{13}\) It is useful to note that the electric field strength starts growing as the ionization wave exits the tube, and depending on the discharge conditions, it reaches the maximal values of several millimeters or more than a centimeter from the exit of the capillary. Furthermore, electric field strength starts to decrease and the discharge vanishes.\textsuperscript{19}\) The reasons for the increase in the electric field is the increase in air admixture in the helium stream and a consequent increase in the density of nitrogen ions, which are main constituents of space charge layer in the streamer head. Also, the contraction of the helium effluent in the flow direction occurs,\textsuperscript{31}\) leading to the decrease in the streamer radius and the increase in the space charge density. When air entrainment exceeds certain limits, electric field strength becomes insufficient for the direct ionization processes; that is, the value of the Townsend ionization coefficient rapidly decreases. The increase in the electric field strength in the streamer head causes the increase in the electron density, which is in consistence with the outcome of Thomson scattering measurements.\textsuperscript{51} The values obtained with Thomson scattering are higher, and Hübner et al. obtained maximal 1.5 \times 10^{13}\,\text{cm}^{-3} approximately 25\,mm from the tube exit. In our case, a maximal density is below 2 \times 10^{12}\,\text{cm}^{-3}\) 9\,mm from the end of the capillary. At the same position, Thomson scattering gives below 5 \times 10^{12}\,\text{cm}^{-3}.

From the presented analysis, it is reasonable to conclude that the estimated electron density values seem right indicating the differences in the observed discharges. For example, plasma jet investigated by Thomson scattering has a different geometry, powered electrode is placed only 7\,mm from the tube exit, amplitude of the pulsed applied voltage was 7\,kV with the rise time of 150\,ns and duration of 250\,ns. Pulsed voltage with short rise time results in the overvoltage breakdown, which could enhance ionization and excitation processes and cause the increase in all discharge parameters such as electron temperature, electric field, and electron density.\textsuperscript{5}

IV. CONCLUSIONS

This article is devoted to the measurements of the distribution of the electric field in a streamer head in the capillary of helium plasma jet. The values of the electric field are obtained utilizing the Stark polarization spectroscopy method. The experiments were performed for several gas flows in the range of 700–2000 SCCM. Using the experimentally obtained values of the electric field, electron density distributions are estimated on the basis of existing streamer theory.

The following facts are revealed by this article:

(i) The electric field has its maximum in the vicinity of the grounded ring electrode and decreases as the ionization wave moves toward the end of the dielectric tube. It starts from 10–11\,kV/cm in the vicinity of the grounded electrode and ends with 5–7\,kV/cm, which is close to the lower limit for streamer propagation in helium. The possible reason for the electric field decrease is charging of the inner walls of the dielectric tube, which leads to electric potential screening.

(ii) The gas flow rate influences the electric field distribution, but the values near the grounded ring and at the exit of the tube remain similar for all gas flows. Higher gas flow rates, 1500 and 2000 SCCM, cause the appearance of the bright discharge region around the center of the tube. Such phenomena cause local maximum in the spatial distribution of the electric field in the ionization wave front. Regardless of these occurrences, electric field strength decreases again after the mentioned peak and the electric field in the streamer ends with similar values as in the case of lower flow rate.

(iii) Electron density distribution in the streamer channel can be estimated if the values of the electric field strength in the streamer head are known. Existing streamer theory connects the electron density in the plasma with the electric field strength in the streamer head and the electric field dependent Townsend...
ionization coefficient. In such a way, estimated electron concentration has a maximum of $4 \times 10^{11}$ cm$^{-3}$ near the grounded ring and decreases for an order of magnitude as the ionization wave approaches to the capillary nozzle. The dependence of the electron density on the gas flow rate has a similar trend as the dependence of the electric field strength.

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