Spatial and Excitation Variations for Different Applied Voltages in an Atmospheric Neon Plasma Jet*

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Abstract A neon plasma jet was generated in air, driven by a 9 kHz sinusoidal power supply. The characteristics of the plasma plume and the optical spectra with plasma propagation for different applied voltages were investigated. By increasing the applied voltage, the plasma plume first increases and then retracts to become short and bulky. The shortened effect of Ne plasma plume (about 10 mm) for the further voltage increasing is more apparent than that of He (about 3 mm) and Ar (about 1 mm). Emission intensity of the N\textsubscript{2} (337 nm) increases with the applied voltage, gradually substituting the emission intensity of Ne (702 nm and 585 nm) as the noticeable radiation. At the nozzle opening, the Ne (702 nm) emission dominates, while the Ne (585 nm) emission is most noticeable around the tip of the plasma plume. The spatial distribution of the three spectral lines indicates that Ne (702 nm) emission decreases dramatically with plasma propagation while Ne (585 nm) and N\textsubscript{2} (337 nm) emissions reach their maxima at the middle of the plasma plume. The results indicate that the Ne (702 nm) emission is much more sensitive to the average electron temperature and the density of the high-energy electrons, so it changes greatly at the tube nozzle and little at the tip region as the voltage increases. The population of high-energy electrons, the average electron temperature, the collision with air molecules and the Penning effect between Ne metastables and air molecules may explain their different variations with plasma propagating and voltage increasing.

Keywords: neon plasma jet, optical spectrum, plasma plume, emission variation

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(Some figures may appear in colour only in the online journal)

1 Introduction

Atmospheric pressure plasma jets (APPJ) have recently attracted significant attention, due to their non-thermal mechanisms and corresponding effects, especially useful for biomedicine, environmental protection and material modification\cite{1}. An APPJ generates a non-thermal plasma in open air rather than in confined discharge gaps or in sealed vessels at low pressure. Therefore, it obviously has the ability to make various applications easier and more convenient. Many experiments based on the helium (He) and argon (Ar) noble gases, or their mixtures with N\textsubscript{2} and O\textsubscript{2}, were made in the past to investigate the plasma discharge mechanisms, especially the propagation along the noble gas channel, simultaneously with the diffusion into the open air\cite{2-4}. However, there are only a few reports on the propagation of neon (Ne) plasma jets\cite{5-7}. Li et al. shows that there are large differences between the optical emission spectra of helium, neon, argon and krypton flow gases, such as that the peak at 391.4 nm only exists for the helium flow gas because the metastable levels of neon and argon are too low to excite the reaction\cite{5}. Lei et al. shows that neon optical spectra focus on the range of 550–850 nm and the neon plasma jet length increases with the voltage increasing\cite{6,7}. As excited metastable neon atoms may interact directly with ground state diatomic oxygen molecules to produce O\textsuperscript{2+}, and O, neon is considered to be useful as the feeding gas in a plasma jet device. In this article, we present a Ne-APPJ driven by a sinusoidal alternating current (AC) high-voltage power supply, to show the optical characteristics and discharge relations of neon and air. The saturation effects with the voltage increasing and the particular change of different neon spectral lines with the plume positions (different with helium and argon plasma jets) are shown in this article. The spatial variations and excitation characteristics of the N\textsubscript{2} and Ne emissions may be very helpful to understand the discharge mechanisms in plasma jet.

2 Experimental setup

Fig. 1 is a schematic outline of the experimental setup. The plasma jet device used in this study is a
simple structure with a single electrode inserted in a quartz tube, which is placed in a syringe. The inner and outer diameters of the dielectric quartz tube are 2 mm and 4 mm, respectively. The high-voltage electrode is a single copper rod, which is inserted in the quartz tube. The diameter of the copper rod is about 1 mm and is inserted until 1 mm before the tube’s nozzle end. As shown in Fig. 1, the opening position of the tube nozzle is defined as \( z = 0 \) mm for the simplicity of the description. The copper rod is covered with an insulating layer until the \( z = -44 \) mm point, which is indicated in Fig. 1. The electrode is connected to a sinusoidal AC voltage power supply (CTP-2000K/P, Suman, Nanjing), which has a maximum output voltage of 30 kV and a frequency that can be adjustable between 5 kHz and 20 kHz. Neon with 99.99% purity is used as the working gas. The gas flow rate is controlled by a glass rotary flow meter. A digital camera (Canon 60D) is used to take pictures of the plasma plume under different bias conditions, with a 30 s exposure time. The optical spectrum of the plasma plume is recorded with an Ocean Optics (Maya 2000-PRO) spectrometer having 100 ms integration time and a spectral resolution of 0.47 nm. A 2 mm-wide slit, just in front of the plasma plume with 2 mm gap, is placed between the fiber of the spectrometer and the plasma plume. The gap between the plasma plume and the fiber is 10 mm. The diameter of the fiber inlet is 455 \( \mu \)m and the slit of the spectrometer is 25 \( \mu \)m. The voltage is measured through a capacitive divider (1000:1) at the power supply and is recorded by an oscilloscope (Agilent DS06034A).

3 Experimental results and discussions

Fig. 2(a)–(e) show the images of the plasma plume, driven at different applied voltages \( V_{pp} \) (peak to peak voltage). The frequency of the driving voltage waveforms is 8.62 kHz; the neon flow rate is 2.5 L/min. (a) \( V_{pp} = 1.92 \) kV, (b) 3.46 kV, (c) 6.54 kV, (d) 11.0 kV, (e) 18.76 kV

![Fig. 1 Schematic experimental setup and its measurement system](image)

![Fig. 2 Images of the plasma plume at different peak to peak voltages \( V_{pp} \) at a frequency of 8.62 kHz; the neon flow rate is 2.5 L/min. (a) \( V_{pp} = 1.92 \) kV, (b) 3.46 kV, (c) 6.54 kV, (d) 11.0 kV, (e) 18.76 kV](image)
the primary channel. Here, the maximal width of the plasma plume is larger than 3 mm. According to our earlier calculation \[8\], the Ne mole fraction is around 25% at the position \((z=22 \text{ mm}, \Phi=3 \text{ mm})\) under these experimental conditions. It indicates that much more air takes part in the discharge process beside the primary channel. The variation of the plasma jet length in Ne-APPJ is somewhat different from that shown in previous articles on helium and argon atmospheric plasma jets \[9-12\]. In those cases usually the jet length increases with the applied voltage. Maybe it is because the applied voltage used for the helium and argon plasma jet was not high enough to show the saturation effect at higher voltages. In order to verify this point, the experiment was repeated using helium and argon as the working gas respectively. Similar to the neon plasma jet, the voltage is increased high enough to ionize the air in the experiments. Fig. 3(b) shows the comparison of plasma plume lengths as a function of applied voltages among neon, helium and argon plasma jets. As shown in Fig. 3(b), both the helium and argon plasma jet length curves show the saturation effects at higher voltages as we predicted. Also, the helium plasma jet length curve can be divided into four zones like the neon plasma jet. However, the shortened effect of the neon plasma plume (about 10 mm) for the further voltage increasing is more apparent than that of helium (about 3 mm), while the argon plasma plume stays almost stable (about 1 mm) from 20 kV to 30 kV. It is because the voltage is high enough to ionize the air beside the primary channel, but not to ionize the noble gas channel along the tube axis. The slight differences of the saturation effects among the three noble gases may be caused by the different main ionization and excited processes (such as Penning ionization for neon and helium, step ionization for argon) and the gas flow characteristics (gas density, dynamic viscosity, diffusion coefficient, etc.) \[5\].

Fig. 4 shows the optical spectra of the plasma plume just at the tube nozzle (outside the tube) for different applied voltages. Fig. 5 shows the optical spectra of the plasma plume at the tip region for different applied voltages. Both Figs. 4 and 5 show that the bands from air and neon are most intense, such as \(N_2(C^3 \Pi_u \rightarrow B^3 \Pi_g)(316 \text{ nm, } 337 \text{ nm, } 357 \text{ nm, } 380 \text{ nm, } 400 \text{ nm, } 420 \text{ nm})\), \(Ne^{++}(3S_1) \rightarrow Ne^+(1P_1)(585 \text{ nm})\), \(Ne^{++}(3S_1) \rightarrow Ne^+(3P_2)(702 \text{ nm})\), \(Ne^{++}(3D_3) \rightarrow Ne^+(3P_2)(640 \text{ nm})\), \(Ne^{++}(3S_1) \rightarrow Ne^+(3P_2)(724 \text{ nm})\) and \(O(5P_1) \rightarrow O(5S_2)(777 \text{ nm})\) \[13,14\]. Besides the above emissions, NO emission is also observed at high applied voltage, as shown in Fig. 4(c). The intensity of the various emissions is a function of the applied voltage and the spatial positions. The quantum efficiencies of \(N_2(337 \text{ nm})\), \(Ne(585 \text{ nm})\) and \(Ne(702 \text{ nm})\) of the spectrometer are 65%, 77% and 73% respectively. As shown in Fig. 4, the \(N_2(337 \text{ nm})\) replaces the \(Ne(702 \text{ nm})\) to be the noticeable emission line gradually with the increase of the applied voltage due to its faster increasing rate. In Fig. 5, it is shown that the \(N_2(337 \text{ nm})\) also replaces the \(Ne(585 \text{ nm})\) as the noticeable radiation, when gradually increasing the voltage. Ne (702 nm) is the dominating radiation at the tube nozzle, while Ne (585 nm) becomes the dominating radiation around the tip of the plasma plume outside the tube for neon emissions. Comparing Fig. 4 with Fig. 5, it can be seen that the emission intensity of Ne (702 nm) decreases dramatically at the tip region, but the emission intensity of Ne (585 nm) is similar to itself at the tube nozzle.
Fig. 5 Optical spectra at the tip of the plasma plume for different applied voltages: (a) 2.94 kV, (b) 8.32 kV, (c) 15.8 kV, (d) 18.76 kV

Fig. 6 shows the spatially normalized emission intensity of the three main spectral lines $N_2$ (337 nm), Ne (585 nm), Ne (702 nm) at 5.4 kV and 11 kV respectively. It can be seen that Ne (702 nm) declines as soon as the plasma plume propagates in the open air. However, the emission intensities of Ne (585 nm) and $N_2$ (337 nm) first increase and reach their maxima at about 10–15 mm, which is almost the middle of the whole plasma plume. Then they decrease with the further propagation of the plasma in the air. Therefore, the emission intensities of Ne (585 nm) at the tube opening and the tip region are similar as shown in Figs. 4 and 5. Besides, it is noteworthy that Ne (585 nm) and $N_2$ (337 nm) have similar variation trends with spatial positions.

Fig. 7 presents the normalized emission intensity of $N_2$ (337 nm), Ne (585 nm) and Ne (702 nm) at the tube nozzle region and the tip region for different applied voltages. At the tube nozzle, the emission intensity of Ne (702 nm) rises around 7 times and Ne (585 nm) rises around twice when the voltage increases from 1.92 kV to 18.76 kV. At the tip region, the emission intensity of Ne (585 nm) increases around twice while Ne (702 nm) changes little with the voltage increasing. As can be seen in Fig. 6, the emission intensity of Ne (585 nm) at the tube nozzle is similar to that at the tip region.

Fig. 8 shows the excited electron temperature as a function of voltages at the tube nozzle and the tip region of the plasma plume. The excited electron temperature was measured roughly by the relative intensity of two emission lines Ne (702 nm) and Ne (724 nm) \cite{15}, where the associated parameters were obtained from NIST (National institute of standards and technology) data. It can be seen that the excited electron temperature increases with the voltage increasing at the tube nozzle. The maximum value is below $1.5 \times 10^4$ K, which is thought to be the cold plasma range. Meanwhile at the tip region, the electron temperature changes little with only several tens of K.

Fig. 6 The spatial variation of the normalized intensity of $N_2$ (337 nm), Ne (585 nm) and Ne (702 nm) at 5.4 kV and 11 kV respectively. (a) 5.4 kV, (b) 11 kV

Fig. 7 The normalized intensity of the $N_2$ (337 nm), Ne (585 nm), Ne (702 nm) as a function of voltages at the tube nozzle and the tip region of the plasma plume. (a) at the tube nozzle, (b) at the tip region
If it is assumed that the direct electron collision from the ground to the emitting state is the dominant excitation process, and that radiation is the dominant deactivation process, the intensity of the optical emission of a species equates directly to the associated impact inelastic collision reaction \[^{[14]}\]. The measured intensity of the emission line can be expressed by \[^{[14]}\]

\[
I_m = C_m(\varepsilon_e)\eta_m N_m.
\]

The rate coefficient \(C_m(\varepsilon_e)\) is a function of the energy of the electrons \(\varepsilon_e\) which is affected by the discharge parameters. The excitation efficiency \(\eta_m = k_e(\varepsilon_e)n_e\) is a function of the density and energy distribution function of the electrons, since \(k_e(\varepsilon_e)\) is the excitation rate and \(n_e\) is the electron density. \(N_m\) is the concentration of the reactant species.

Therefore, we can see that the emission intensity is related to the concentration of reactant species, the electron temperature, the electron density, and so on. As for the characteristics of the plasma jet, the mixing ratio of the Ne and air is changed with the position of the plasma plume. Also, much more air can be discharged with the voltage increasing because the ionization coefficient has large differences between Ne and air. So it is a complicated system for the plasma discharge.

The mechanisms responsible for neon emission peaks at 585 nm and 702 nm are as follows:

\[
\text{Ne}^{**}(^1S_0)(18.97 \text{ eV}) \rightarrow \text{Ne}^*(^1P_1)(16.85 \text{ eV})
\]

\[ + \hbar\nu(585 \text{ nm}), \quad (2) \]

\[
\text{Ne}^{**}(^3S_1)(18.38 \text{ eV}) \rightarrow \text{Ne}^*(^3P_2)(16.62 \text{ eV})
\]

\[ + \hbar\nu(702 \text{ nm}). \quad (3) \]

According to the excitation levels and corresponding energies, \(\text{Ne}^{**}(^1S_0)(18.97 \text{ eV})\) and \(\text{Ne}^{**}(^3S_1)(18.38 \text{ eV})\) are the highest and lowest excitation levels respectively among 10 levels of \(\text{Ne}^{**}(2p^53p)\). We know that the emission intensity of the spectral line is directly related to the population of the excited state particle at the upper level of the transition. It is also related to the collisional quenching effect and the electron temperature \[^{[16]}\]. As \(\text{Ne}^{**}(^3S_0)\) (18.97 eV) is the highest excitation level among 10 levels of \(\text{Ne}^{**}(2p^53p)\), we suggest that the variation of high-energy electrons with the voltage increasing is more inclined to influence the lower excitation levels of \(\text{Ne}^{**}(2p^53p)\), such as \(\text{Ne}^{**}(^3S_1)(18.38 \text{ eV})\), or directly ionize Ne atoms, or excite to much higher excited energy levels, such as \(\text{Ne}^{**}(2p^55s)\). Therefore, the influence of increasing voltage, which means the higher average electron temperature, may be rather ineffective to Ne (585 nm) emission compared to Ne (702 nm) emission.

At the tube nozzle, the average electron temperature and the population of the high-energy electrons increase with the voltage increasing. Therefore, the emissions of \(\text{N}_2\) (337 nm), Ne (585 nm) and Ne (702 nm) all increase with the voltage increasing. Emission of the \(\text{N}_2\) (337 nm) increases with the applied voltage, gradually substituting the emission of Ne (702 nm) as the noticeable radiation. For small electric fields, \(\text{N}_2\) is more difficult to excite and ionize. With the voltage increasing, much more \(\text{N}_2\) besides the primary channel can be excited and ionized, so the emission of \(\text{N}_2\) (337 nm) gradually substitutes the emission of Ne (702 nm) as the noticeable radiation. In conclusion, the increase of the average electron temperature and the population of the high-energy electrons could explain the increase of the spectral intensities of three spectral lines from Ne and \(\text{N}_2\) at the tube nozzle.

At the tip region, something is different from that at the tube nozzle. The earlier investigation indicates that the potential drop for the finite conductivity in the plasma plume leads to the decrease of the maximal electric field along the propagation direction, then to the decrease of the population of high-energy electrons \[^{[17]}\]. It was pointed out that a cathode-directed streamer propagating into free space will terminate once it has propagated to the point where the voltage is below a certain value \[^{[17]}\]. The tip region is around the region where the plasma propagation stops. Therefore, we suppose that the average electron temperature and the density of the high-energy electrons should not vary so much as that at the tube nozzle with the voltage increasing. It should be noted that much more air takes part in the discharge process beside the primary noble gas channel at the tip region. The increase of the electron collisions with much more \(\text{N}_2\) and the Penning effect result in the increase of \(\text{N}_2\) (337 nm). Therefore, the \(\text{N}_2\) (337 nm) replaces the Ne (585 nm) as the noticeable radiation at the tip region with the voltage increasing. As we just mentioned, the Ne (702 nm) is much more sensitive to the average electron temperature and the density of the high-energy electrons, so it changes much at the tube nozzle and changes little at the tip region with the voltage increasing. At the tip region, the collision with air molecules, the Penning effect between Ne metastables and air molecules could explain the variation of the three line intensities.
With plasma propagation, the emission intensity of Ne (702 nm) decreases dramatically due to the diffusion of the ambient air into the Ne plasma plume. As we know, the average electron temperature and the population of high-energy electrons decrease with plasma propagation. Therefore, Ne (702 nm) declines as soon as the plasma plume propagates in the open air. Besides, the reduction of Ne$^{+*}(3S_1)(18.38 \text{ eV})$ particles through the collisional quenching effect with the air molecules may partly cause the decay of Ne (702 nm). With plasma propagation, the emission intensity of N$_2$ (337 nm) first increases and reaches its maxima at the middle of the plasma plume. It is because the N$_2$ percentage is rather low at the tube nozzle, and increases with the plasma propagation. The increase of the electron collisions with much more N$_2$ and the Penning effect result in the increase of N$_2$ (337 nm). After it reaches the maxima, the decrease of Ne metastables population and the decrease of the high-energy electrons play a dominant role and lead to the decay of N$_2$ (337 nm). More theoretical and experimental investigations would be carried out for understanding the variation of the spectral lines deeply in the next work.

4 Conclusions

In summary, an atmospheric neon plasma jet driven by a sinusoidal AC high voltage power supply was investigated. Both the plasma jet length and the optical spectra characteristics of N$_2$ and Ne vary with the applied voltage in a way that differs from those of previous publications of helium and argon plasma jets. In the case of the neon plasma jet in air, we observed an optimum voltage of 16 kV, producing a plasma jet length of 38 mm excluding the plasma plume in the upstream region. The saturation effects with the voltage increasing and the particular change of different neon spectral lines with the plume positions have been observed in this article. The population of high-energy electrons, the average electron temperature, the collision with air molecules and the Penning effect between Ne metastables and air molecules may explain their different variations with the voltage increasing and the plasma propagating. The spatial variations and excitation characteristics of the N$_2$ and Ne emissions are helpful to understand the discharge mechanisms in a plasma jet.

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References


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