An Atmospheric Large-Scale Cold Plasma Jet

LV Xiaogui (吕晓桂), REN Chunsheng (任春生), MA Tengcai (马腾飞), FENG Yan (冯岩), WANG Dezhen (王德真)

1 College of Science, Inner Mongolia Agricultural University, Hohhot 010018, China
2 School of Physics and Optoelectronic Technology, Dalian University of Technology, Dalian 116024, China

Abstract This letter reports on the generation and characteristics of a large-scale dielectric barrier discharge plasma jet at atmospheric pressure. With appropriate parameters, diffuse plasma with a 50×5 mm² cross-sectional area is obtained. The characteristics of the discharges are diagnosed by using electrical and optical methods. In addition to being generated in helium, plasma is also generated in a mixed gas of helium and oxygen. The oxygen atomic radiant intensity (3p5P→3s5S, 3p3P→3s3S transition) is not proportional to the proportion of oxygen in the gas mixture, as shown by the experimental results.

Keywords: dielectric barrier discharge plasma jet, atmospheric air, large-scale

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1 Introduction

Enjoying an exponential growth in its applications, atmospheric pressure glow discharge (APGD) has recently received remarkable attention [1∼4]. However, at one atmospheric pressure, due to the relatively high breakdown voltage of working gases, the discharge gaps are normally less than several centimeters, which limits the size of objects to be treated [5]. Besides, if remote exposure (indirect treatment) is used, some short lifetime active species may already disappear before reaching the samples [6]. Because of the merit of the plasma jets, which generate plasmas in an open space (surrounding air) rather than confined in discharge gaps, many potential applications become possible [7∼10]. However the diameters of APGD jets typically cover only a few millimeters and, as such, are too small for large-scale applications such as surface coating, deposition and cleaning. To address these concerns, a solution grouping many APGD jets together to form an array of a longer length scale has been operated [11∼15].

In this letter, we report a large-scale dielectric barrier discharge plasma jet with 50×5 mm² area generated in a rectangular cross-sectional quartz tube at atmospheric pressure. With an appropriate adoption of important parameters, such as applied voltage, frequency and gas flow rates, a diffuse plasma is obtained. Working with this device, atmospheric pressure cold plasma with advantages of a larger scale and better uniformity, which is very important for its application, can be obtained. The characteristics of the discharges are diagnosed by electrical and optical methods. In addition to being generated in helium, plasma is also generated in a mixed gas of helium and oxygen. The oxygen atomic radiant intensity (3p5P→3s5S, 3p3P→3s3S transition) is not proportional to the proportion of oxygen in the gas mixture, as shown by the experimental results.

2 Experimental setup

The experimental scheme is shown in Fig. 1. The gas discharge system adopts a rectangular cross-sectional quartz tube with an internal cross-sectional area of 50×5 mm², the open end of which is wrapped by copper wires serving as the powered electrode. A stainless steel plate covered with a quartz layer with a thickness of 1 mm is placed 7 mm away from the open end of the quartz tube and used as the grounded electrode. The system is driven by a sinusoidal AC supply with a peak voltage of 0∼10 kV and a frequency varying from 10 kHz to 60 kHz. By applying a high voltage between the two electrodes, plasma with the working gas of He (99.99%) is generated in the ambient air. The discharge current is measured through a 100 Ω resistor which is connected in series with the grounded electrode by a voltage probe (P6139A, Tektronix). The voltage measurements are made by using a high-voltage probe (P6015A, Tektronix) and the data recorded by using a storage oscilloscope with a bandwidth of 1.0 GHz (DOP 4104, Tektronix). A digital camera (Finepix s602z) is used to take the pictures of the discharge with an exposure time of 1/6 s. The optical emission spectra are measured by using a spectrometer (Acton Research Spectrum-250i).
3 Results and discussion

When helium with a flow rate of 0.22 m³/h is injected into the tube and a voltage with amplitude up to 2.3 kV, frequency up to 14.7 kHz, is applied to the high voltage electrodes, a homogeneous plasma, the cross-sectional area of which is equal to that of the nozzle, is generated in front of the end of the quartz tube in the surrounding air, as shown in Fig. 2. Fig. 3 shows the traces of the applied voltage and the total current. There is one current pulse at every half cycle of the applied voltage, similar to the dielectric-barrier discharge [3]. Oxygen is then added into helium to generate more reactive oxygen species, which play a significant role in sterilization, polyimide etching, etc. With a fixed frequency and fixed helium gas flow value, we inject oxygen with different flow rates into the tube together with helium and by keeping the applied voltage amplitudes equal at about 2.4 kV, homogeneous plasma can be generated. Fig. 4 shows a photo of the discharge with the mixed oxygen flow rate of 1.2 cm³/min. It deserves to be specially noted that homogeneous plasma can be maintained only when the applied voltage amplitude and repetition rate fall within a narrow range, and the uniformity of the discharge is destroyed if either of the two parameters mentioned above increases.

The optical emission spectra from 700 nm to 850 nm were measured for the plasma outside the tube generated with different oxygen concentrations. Fig. 5(a) and Fig. 5(b) show the emission spectrum lines corresponding to Fig. 2 and Fig. 4, respectively. It clearly indicates that both jets have significantly stronger emission atomic O lines at 777.4 nm and 844.6 nm, and He at 706.5 nm. To compare the O atom concentration of jets generated in different conditions, we calculate the ratios of the intensity of the O atom line at 777.4 nm (3p5P → 3s5S transition) and 844.6 nm (3p3P → 3s3S transition) to that of the He atomic line at 706.5 nm, and the results are shown in Fig. 6. From Fig. 6 we can see that the two curves follow the same variation tendency and reach their maximum at the same oxygen concentration of 0.032 vol%. After that, the ratios decrease as the oxygen concentration increases. Even when the oxygen concentration is increased up to 0.081 vol%, the value of 777(nm)/706(nm) is less than that in the case without oxygen addition. We attribute it mainly to the competition between the generation of the O atom in the corresponding excited state by electron impact dissociation, which increases with more O₂ molecules participating in this process, and the electron density involved in the electron impact dissocia-
tion, which decays in the process of electron attachment to O$_2$ molecules with increasing O$_2$ concentration.

![Fig.5](image_url)

**Fig.5** The emission spectrum lines: (a) corresponding to Fig. 2 and (b) corresponding to Fig. 4

![Fig.6](image_url)

**Fig.6** The relationship between the ratios of the intensity of O atomic line at 777.4 nm and 844.6 nm to that of He atomic line at 706.5 nm and the O$_2$ concentration of the mixed gas (color online)

4 Conclusions

In summary, a large-scale diffuse plasma with a 50×5 mm$^2$ cross-sectional area is obtained with a helium flow rate of 0.22 m$^3$/h, voltage amplitude up to 2.3 kV and repetition rate up to 14.7 kHz in a rectangular cross-sectional quartz tube. The traces of the applied voltage and the total current are similar to the dielectric barrier discharge. The uniform plasma can also be generated when oxygen is added. The oxygen excited atom (3p5P $\rightarrow$ 3s5S, 3p3P $\rightarrow$ 3s3S transition) density is not proportional to the proportion of oxygen in the gas mixture, as shown by the experimental results.

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E-mail address of corresponding author

REN Chunsheng: rchshen@dlut.edu.cn