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Characteristic study of cold atmospheric argon plasma jets with rod-tube/tube high voltage electrode

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ABSTRACT

Atmospheric argon plasma jets are generated with the rod-tube/tube high voltage electrode and a ring ground electrode at 8 kHz sinusoidal excitation voltage. It is found that the vibrational temperature, electronic excitation temperature, atomic oxygen density and spectral intensity with the rod-tube high voltage electrode are enhanced significantly than that with the tube high voltage electrode. The atomic oxygen density, molecular nitrogen density, and average electronic density are about magnitude of 10^{16} cm^{-3}, 10^{15} cm^{-3}, and 10^{12} cm^{-3} respectively, and the excited Ar, N_2, OH and O are presented in the plasma plume with the rod-tube/tube high voltage electrode.

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1. Introduction

Low temperature atmospheric plasma jets have received much attention recently from several emerging novel applications such as materials processing [1], thin film deposition [2–4], etching [5], sterilization [6–10], and surface modification [11]. The plasma jets are usually formed in open space surrounding air and have chemically active species such as OH and O.

Such an atmospheric plasma jets have been generated by the various electrode configurations and the generators. For example, Erdinc Karakas and Mounir Laroussi [12] used the plasma pencil to measure the plasma bullet lifetime and its velocity. The plasma pencil was made of hollow dielectric tube with two copper ring electrodes attached to the surface of centrally perforated dielectric disks separated by 5 mm. A unipolar square high voltage (HV) pulse in the order of 4.0–7.5 kV was applied to the high voltage electrode. Chiang et al. [13] presented the nitrogen-based dielectric barrier discharge plasma jet device, which was driven by a quasi-pulsed bipolar power supply (Model Genius-2, EN Technologies, Inc.) at a fixed frequency of 60 kHz. The plasma jet device was made of two parallel copper plate electrodes with embedded cooling water and the copper plate electrodes were covered with quartz plate. Lu et al. [14] presented an RC plasma jet, which could be touched by bare hands and could be directed manually by a user to place it into root canal for disinfection without causing any painful sensation. The main body of plasma jet device was made of a medical syringe and a needle. The needle was used for guiding the gas flow and also served as the electrode, which was connected to a high voltage (HV) submicrosecond pulsed direct current power supply through a 60 kΩ ballast resistor *R* and a 50 pF capacitor *C*, where both the resistor and the capacitor were used for controlling the discharge current and the voltage on the needle. Deng et al. [15] investigated bacterial inactivation by atmospheric pressure dielectric barrier discharge plasma jet. The main body of plasma jet reactor was made of a quartz condenser tube used as the dielectric layer. The sodium chloride (NaCl) solution in the outer layer of the reactor was acted as the external electrode to ground. The internal electrode was a copper rod to connect the alternating current (AC) power supply operated between 16 and 20 kHz.

It is well known that dielectric barrier discharge (DBD) configuration is to prevent the transition to spark and to homogenize the discharge. In this paper, cold atmospheric argon plasma jets are generated with the rod-tube/tube high voltage electrode and a ring ground electrode in DBD, which are powered by a sinusoidal excitation voltage at 8 kHz. The aim of this work is the discharge characteristic study of the plasma jets generated with the rod-tube/tube high voltage electrode, such as the applied voltage, conduction current, and displacement current waveform are determined by

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digital oscilloscope and equivalent circuit, and the gas temperature, excitation temperature, atomic oxygen density, molecular nitrogen density, and average electronic density are obtained by optical emission spectroscopy.

2. Experimental setup

A schematic of experimental apparatus and discharge photograph are shown in Fig. 1. In Fig. 1(a), first high voltage electrode is a stainless steel tube with outer diameter of 8 mm, inner diameter of 6 mm, and length of 128 mm. The second high voltage electrode is a stainless steel rod with diameter of 2 mm, length of 200 mm, and a pencil-shaped tapered end, which is inserted into stainless steel tube. The tapered end of rod protrudes 7 mm from the bottom end of tube electrode and the rod-tube/tube (without the rod) high voltage electrode is powered by a sinusoidal excitation voltage at 8 kHz. The tube electrode is tightly covered by a quartz glass tube with outer diameter of 10 mm, inner diameter of 8 mm, and length of 100 mm. The open end of quartz glass tube is a pencil-shaped tapered end as the gas outer hole, the diameter of which is 2 mm. A copper foil of 20 mm length is wrapped tightly on the outside of the quartz glass tube as the ring ground electrode, and which away from the gas outer hole is 10 mm. The bottom end of tube electrode is at the same height with the top end of ground electrode. A quartz glass plate (thickness of 1 mm) is placed in the position of 5 mm away from the gas outer hole.

The working gas of Ar (99.999%) is injected through the tube power electrode controlled by mass flow controller at Ar flow rate of 1 lpm. The applied voltages are measured by using a high voltage probe (Tektronix P6015A) and the currents are measured through a 50 Ω resistor in series with the ground electrode, and the electrical signals are recorded via a digital oscilloscope (Tektronix TDS2012B). An optical fiber located in the position of 2 mm away from the quartz glass plate is used to collect the optical emission of the plasma plume and the signals are recorded by a spectrometer (Acton INS-300-122B) with a grating of 1200 grooves per millimeter and slit width of 20 μm. The spectrometer allows that the spectrum can be measured by hardware model and software model, respectively. In hardware model, the noise signal of spectrum is small, but the spectrum is easily saturated and can be solved by adjusting the pixels. Due to the difference of the pixels, the spectral intensity can not be compared between that with the rod-tube high voltage electrode and with the tube high voltage electrode. Accordingly, the spectral intensity is compared by software model, in which the saturation problem of spectrum is not appeared, but the noise signal of spectrum is relatively larger than that in hardware model. In this paper, all calculating and simulating involved spectrum is obtained by hardware model and the discharge images are taken by a Nikon digital camera COOLPIX S600.

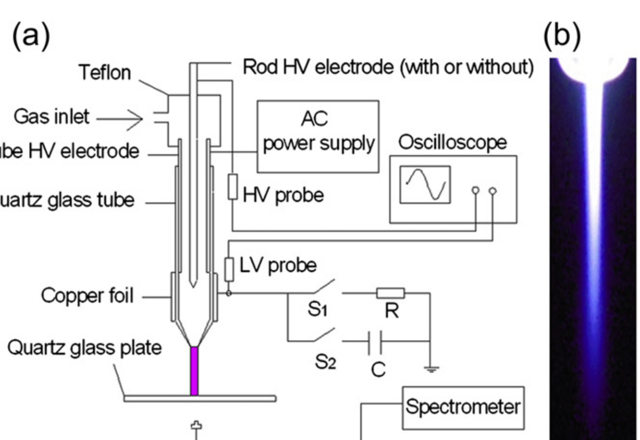

Fig. 1. Experimental setup of the device (a) and discharge photograph at peak applied voltage of 6.2 kV and Ar flow rate of 1 lpm with the rod-tube high voltage electrode (b).

3. Experiment results and discussion

3.1. Electrical discharge characteristics

It is well known that applied voltage and gas flow rate have a great influence on the length of atmospheric pressure plasma jet [16]. In this work, the plasma jet length versus Ar flow rate at peak applied voltage of 6.2 kV and versus peak applied voltage are measured by discharge images, as shown in Fig. 2. As regards Fig. 2(a), the lengths of the plasma jets increase with the Ar flow rate from 0.5 lpm to 1 lpm and decrease quickly with the Ar flow rate from 1 lmp to 3 lpm. The lengths of plasma jets saturate when the Ar flow rate exceeds 3 lmp. The peak values of plasma jet lengths appear at Ar flow rate of 1 lpm and the peak value with the rod-tube high voltage electrode is 2.3 mm larger than that with the tube high voltage electrode. In Fig. 2(b), the plasma jet lengths increase with the peak applied voltage from 4.6 to 6.2 kV and saturate when the peak applied voltage exceeds 6.2 kV with the rod-tube/tube high voltage electrode.

The conduction current is very important for dielectric barrier discharge, because the effective power and the voltage of gas gap and barrier can be determined by the conduction current [17]. Accordingly, the conduction current in this work is determined by the equivalent circuit diagram shown in Fig. 3. According to the schematic of an asymmetric single dielectric barrier plasma actuator reported by Singh and Roy [18], we have imposed a virtual electrode parallel to the ring ground electrode over the dielectric surface. There are two capacitive components: one is between the rod-tube high voltage electrode and the ring ground electrode C_d (which involves the two capacitive components: one is between the rod high voltage electrode and the ring ground electrode and another is between the tube high voltage electrode and the ring ground electrode, and they are in parallel) and another is between the virtual electrode and the ring ground electrode C_{dv}. The C_p and R_p are the equivalent capacitor and resistor of the plasma, respectively. In fact, the C_p and R_p also involves two components: one is the equivalent capacitor and resistor of the plasma generated by the rod high voltage electrode and another is the equivalent capacitor and resistor of the plasma generated by the tube high voltage electrode, and they are in parallel. The equivalent circuit of the plasma jet device is essentially a capacitor C_p in series with a resistor R_p and a capacitor C_{dv}, and a capacitor C_d parallel to the full circuit with the rod-tube/tube high voltage electrode. In Fig. 3, $U_{tot}(t)$, $I_{tot}(t)$, $I_{dc}(t)$ and $I_{dp}(t)$ are the total applied voltage, total current, conduction current and displacement current, respectively. Using Kirchoff's theorem for the equivalent circuit given in Fig. 3, following equations are obtained:

$$\frac{dU_{tot}(t)}{dt} = \frac{I_{dp}(t)}{C_d}, \tag{1}$$

$$I_{tot}(t) = I_{dp}(t) + I_{dc}(t). \tag{2}$$

where, Eqs. (1) and (2) are used to determine the conduction and displacement current when peak applied voltage is higher than 3 kV. Fig. 4(a) shows the waveforms of applied voltage and displacement current in peak applied voltage of 2 kV. As regarding

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