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Optical investigation of a plasma jet generated by water electrodes at atmospheric pressure

Yongjie Wang*, Zengqian Yin, Huijuan Wang, Zhanlong Zhao

Department of Mathematics and Physics, North China Electric Power University, Baoding 071003, China

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ABSTRACT

A quartz tube tightly surrounded by transparent water electrodes is employed to generate an argon plasma jet at atmospheric pressure. By using electrical and optical diagnosis, the discharge characteristic of the plasma jet is investigated. With the increasing of the gas flow rate, the plasma jet undergoes the transition from laminar to turbulent flow. It is found that the length of the plasma jet increases first and then decreases when the gas flow rate increases from 0.5 L/min to 5.0 L/min. The discharge is composed of several wide low amplitude pulses at the rising voltage edge and one narrow high amplitude pulse at the falling voltage edge. Optical emission spectroscopy is used to diagnose the plasma parameters. It is found that the excited electron temperature and the electron density increase with the increasing of the gas flow rate. These results are analyzed qualitatively.

1. Introduction

Atmospheric plasma jets (APPJs) can generate low-temperature plasma with reactive species in ambient air, and they have the great flexibility of treating the targets from a distance. Due to the ability, the APPJs have recently attracted significant attention for their potential applications in material growth, biomedical applications and pollution control [1–5]. In the meantime, many investigations have been carried out for developing the APPJs with different electrode configurations. According to the relative directions between the applied electric field and the flow field, the plasma jet devices are generally divided into two categories. One type is the cross-field configuration as the electric field is perpendicular to the flow field. The other is the linear-field configuration, in which the electric field is parallel to the gas flow [6]. Walsh and Kong found that the linear-field jet could achieve more active plasma chemistry in the downstream region [6]. Jiang et al compared the discharge behaviors of APPJs with single dielectric, double dielectric and single bare metal electrodes, and found that the single bare metal electrode could generate comparable jet length at a significantly reduced voltage [7]. For a given electrode configuration, besides the operating parameters such as the driving frequency and the working gas, the ambient dielectric can also influence the discharge characteristics [8–11]. Song et al found that the increasing of the dielectric polarization could increase the discharge current and the bullet velocity [12]. Generally, the above mentioned electrodes are made of solid metal, and the light can not pass through the metal electrodes. So the optical emission signals from plasma can not be detected at the locations of the metal electrodes. In addition, the dielectric tube can not be tightly wrapped by the solid metal electrodes. That is to say, the ambient air between the dielectric tube and the metal electrodes, not the working gas, consumes some unnecessary energy, leading to the waste of the input energy. In recent years, transparent electrodes

* Corresponding author.
E-mail address: yjwanghd@126.com (Y. Wang).

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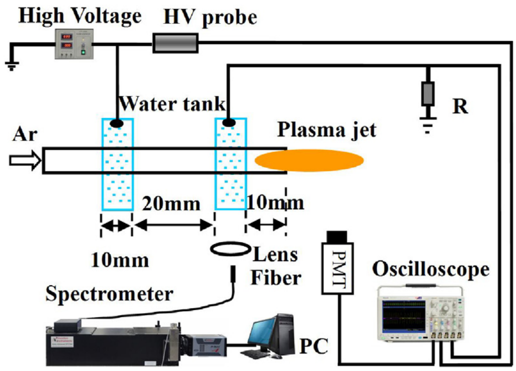

Fig. 1. Schematic diagram of the experimental setup.

have been reported to generate plasma jet [13–18]. Wang et al studied the discharge characteristics in the electrode-water-electrode system [13]. Hwang et al investigated the effects of plasma discharge on bacterial inactivation by using water electrode [14]. Chang et al reported the dynamic evolution of the plasma jet and analyzed the optical signals beneath the ITO-PET electrodes [15,16]. In order to investigate the optical properties of APPJ generated by transparent electrodes, it is necessary to measure the plasma parameters such as electron temperature and electron density, which are very important in the industrial applications of surface modification and biomedicine.

In this paper, a dielectric barrier discharge system with transparent water electrodes is developed to generate APPJ, where a quartz tube is tightly wrapped with the water electrodes. The effect of the gas flow rate on the discharge characteristics is investigated, and the plasma parameters are diagnosed by optical emission spectrometry.

2. Experimental setup

Fig. 1 shows the schematic diagram of the experimental setup. The transparent electrodes are composed of a quartz tube and two water tanks. The outer and inner diameter of the quartz tube is 3.4 mm and 1.8 mm, respectively. The water tank is made of Polyethylene terephthalate (PET) with thickness of 0.5 mm. The top and side views of the water tank are rectangle (10 mm × 40 mm) and square (40 mm × 40 mm), respectively. There is one hole in the left and right sides of the water tank, in which the hole is used for the quartz tube passing through the water tanks. The water tanks are filled with deionized water (conductivity, 2.35 μs/cm) to submerge the quartz tube. A conductivity meter (DDS-307A) is used to measure the conductivity of the water. A copper wire is installed into the water tank and connected to the power supply (Suman CTP-2000K) with a maximum power of 500 W, whose operational frequency fixed at 10 kHz. The quartz tube is immersed in the water tanks, and it is utilized for guiding of the plasma jet. So the water tanks are called transparent water electrodes. The gas gap width between the two water electrodes is 20 mm and the grounded electrode is 10 mm away from the nozzle of the tube. Argon (purity, 99.99%) is used as the working gas, and its gas flow rate is controlled by a mass flow controller. The amplitude of the discharge voltage is measured by a high-voltage probe (Tektronix P6015A, 1000×). A small resistor (50 Ω) in series with the grounded electrode is used to measure the discharge current. The discharge voltage and current are recorded by a digital oscilloscope (Tektronix DPO4054). A digital camera (Canon PowerShot G16) is used to record the time-averaged images. A photomultiplier tube is used to investigate the light emission of the plasma jet. The optical emission spectrum is measured by a spectrometer (ACTON SP2750).

3. Results and discussion

Fig. 2 shows the evolution of the plasma jet with the gas flow rate. When the gas flow rate is 0.5 L/min, the plasma extends outside the quartz tube, and a plasma jet is formed. With the increasing of the gas flow rate, it is found that the light intensity of the discharge increases and the conically shaped plasma jet increases in length. The plasma jet achieves its maximum length at 3.0 L/min. Then, the length of the plasma jet is shortened with a further increasing of the gas flow rate. Although the length becomes short, the radius of the conical plasma jet increases. This indicates that the jet features show a strong dependence on the flow rate.

In order to investigate the evolution of the plasma jet, the length of the plasma jet is measured. Fig. 3(a) gives the plasma jet length as a function of the gas flow rate. At a lower gas flow rate, the length of the plasma jet increases with the gas flow rate. Then, the jet reaches the maximum length of 2.2 cm at a threshold value of 3 L/min. However, a further increasing of the gas flow rate leads to the decreasing of the jet length. To better understand the influence of the gas flow on the plasma jet length, the Reynolds number $Re = \rho v d/\mu = 4\rho Q/(\pi d\mu)$ is employed as the criterion to judge the flow stage for the plasma jet, where ρ is the density of the argon at room temperature, Q is the gas volume flow rate, d is the inner diameter of the quartz tube, and μ is the viscosity of Ar. Fig. 3(b) presents the Reynolds number as a function of the gas flow rate. At the