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Optical and application study of gas–liquid discharge excited by bipolar nanosecond pulse in atmospheric air

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HIGHLIGHTS

- A bipolar nanosecond pulse with 20 ns rising time is employed to generate air gas–liquid diffuse discharge plasma with room gas temperature in quartz tube at atmospheric pressure.
- The plasma gas temperature is determined to be approximately 390 K.
- Bipolar nanosecond pulse discharge is used to treat drinking water, which performs high sterilization efficiency in killing the common microorganisms.

GRAPHICAL ABSTRACT

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ABSTRACT

In this study, a bipolar nanosecond pulse with 20 ns rising time is employed to generate air gas–liquid diffuse discharge plasma with room gas temperature in quartz tube at atmospheric pressure. The image of the discharge and optical emission spectra of active species in the plasma are recorded. The plasma gas temperature is determined to be approximately 390 K by compared the experimental spectra with the simulated spectra, which is slightly higher than the room temperature. The result indicated that the gas temperature rises gradually with pulse peak voltage increasing, while decreases slightly with the electrode gap distance increasing. As an important application, bipolar nanosecond pulse discharge is used to sterilize the common microorganisms (*Actinomycetes*, *Candida albicans* and *Escherichia coli*) existing in drinking water, which performs high sterilization efficiency.

Introduction

Non-thermal atmospheric pressure plasma has recently attracted considerable interest due to its important application values in the field of bacterial or fungal inactivation [1–3], surface modification of polymers [4,5], blood coagulation [6] and decomposition of volatile organic compounds [7,8]. Especially, the low-temperature plasmas were supposed to be beneficial for healthcare in areas of medicine, food safety and fungal inactivation. Wang et al. [9] designed a stable surface barrier discharge device for large-area sterilization applications using a sinusoidal ac high-voltage in air, N_2 and O_2, respectively. The study by Perni et al. [10] indicated oxygen atoms are identified as a major contributor in plasma inactivation using *Escherichia coli* K-12 mutants as biosensors in the gas of He and the mixture of He and O_2, respectively. Laroussi et al. investigated the effect of plasma exposure on the biochemical pathways of bacteria [11].

As one of the most effective methods to generate non-thermal plasma, nanosecond pulsed dielectric barrier discharge (NPDBD) has attracted considerable interest in the last few years [12–14]. A NPDBD is characterized by a fast rising time of pulse voltage,

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which makes the electrical energy delivered in the plasma discharge deposited mainly in the energetic electrons instead of heating the heavy particles [15], so NPDBD exhibits many unique advantages over other discharge types, e.g., high energy transfer efficiency, high electron density, high electron mean energy, and low gas temperature, etc. What's more, NPDBD is an effective method to prevent glow-to-arc transition (GAT) with optimization of the ionization efficiency at atmospheric pressure (AP) [16], so glow discharge can be generated even when the current density is above the threshold for GAT [17].

In this work, a gas–liquid diffuse discharge with low gas temperature is developed by employing a bipolar nanosecond pulse at a large electrode gap distance and a wide varying range of pulse peak voltage. The image of the discharge and optical emission spectra of active species in the plasma are recorded. The effects of pulse peak voltage and electrode gap distance on the emission intensities of N_2 ($C^3\Pi_u \rightarrow B^3\Pi_g$), N_2^+ ($B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+$, 0–0) and OH ($A^2\Sigma \rightarrow X^2\Pi$, 0–0) are discussed. In addition, the rotational temperature (T_{rot}) and vibrational temperature (T_{vib}) of bipolar nanosecond pulse discharge (BNPD) plasma are determined, and the effects of pulse peak voltage and electrode gap distance on the rotational temperature and vibrational temperature are also investigated. In the end, common microorganisms (*Actinomycetes*, *Candida albicans* and *E. coli*) existed in drinking water are sterilized by BNPD plasma, as an application of this form discharge plasma.

Experimental setup

The experimental setup is illustrated schematically in Fig. 1(a), which is composed of a bipolar nanosecond pulsed power supply, a discharge reactor, and an optical detection system. The bipolar nanosecond pulsed power, which is switched by rotary spark gaps and consists of the pulsed capacitors (C_p) repeatedly charged by the storage capacitors (C), can supply a high voltage pulse with a rising time of approximate 20 ns, a pulse width about 60 ns and an adjustable repetition rate in range of 0–400 Hz. A needle electrode and a quartz tube with water are fixed on the center of the stainless-steel plate with a diameter of 30 mm. The needle electrode is made of stainless-steel with a diameter of 0.8 mm, whose tip is sharpened and rounded. The external diameter and inner diameter of the quartz tube are 12 mm and 10 mm, respectively. For reducing the electromagnetic interferences of discharge pulses on the detection system and other instruments, the high-voltage nanosecond pulsed power supply and the measure system are placed in a two-layer shielding box. The pulsed power supply and the reactor are connected to the ground separately. In order to focus the emission light into the optical fiber, a convergent lens is placed parallel to the plate electrode surface in front of the quartz tube. The optical emission spectra (OES) emitted from the discharge region are collected by an Andor SR-750i grating monochromator (grating groove is 2400 lines/mm^{-1}, glancing wavelength is 300 nm). After the diffraction of the grating, the output spectral light can be converted into a digital signal by CCD and to be stored by a computer.

Results and discussion

The visualization and electrical behavior of BNPD at AP

Fig. 1(b) shows an image of BNPD captured by a Cannon 550D digital camera with an exposure time of 500 ms, when the pulse peak voltage, pulse repetition rate, and electrode gap distance are kept at 30 kV, 150 Hz, and 5 mm, respectively. Different with the discharge excited by sine AC voltage, the BNPD between the needlepoint and the surface of water is diffuse and gentle, and no filamentary discharge channels can be observed by the naked eyes. Near the water surface, the plasma has the most cross section area and can almost cover the whole liquid surface. From the needle electrode to the water surface, the discharge luminous intensity in vertical direction declines gradually and the discharge uniform increases, but the discharge area in horizontal direction gradually enlarges.

Fig. 2(a) and (b) shows the waveforms of pulse voltage and discharge current, it is clearly shown that the rising time of the pulse voltage is about 20 ns, and there is only one current pulse with the width of about 40 ns appeared in each voltage pulse. Therefore the duration time of each breakdown is only several tens nanosecond, which is less than the thermal instability time of gas discharge [17]. However, the short rising time and short discharge duration can prevent GAT effectively with optimization of the ionization efficiency [18], the voltage of whole discharge gap can exceed the breakdown voltage in several nanoseconds. What's more, the quartz tube can be considered as a small capacitor in the discharge equivalent circuit, which is shown in Fig. 2(c). Similar with the dielectric barrier discharge, the current density cannot increase unlimited when the pulse voltage raises, therefore the local thermal equilibrium plasma can be prevented effectively and diffuse bipolar nanosecond pulse discharge plasma (BNPDP) can be generated stably in the quartz tube.

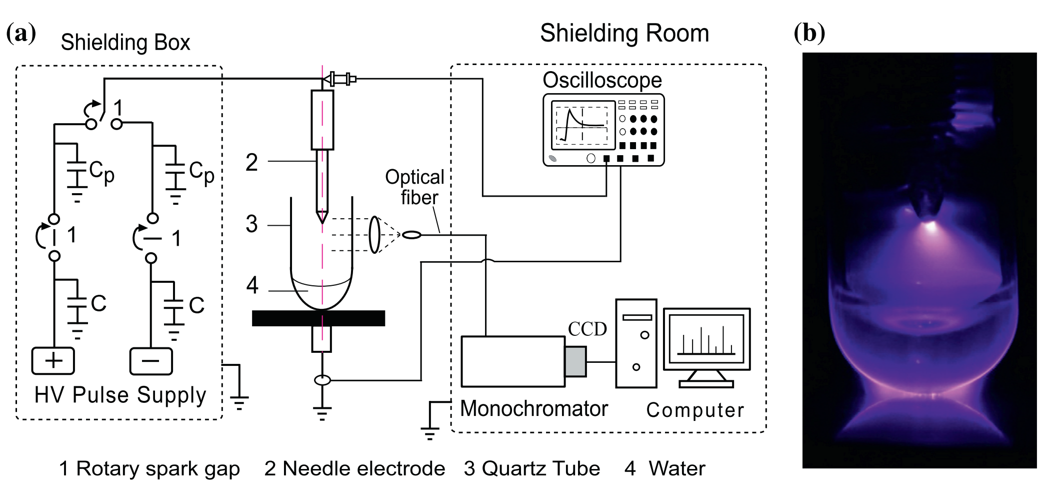

Fig. 1. (a) Schematic of the experimental setup. (b) The image of discharge with 30 kV pulse peak voltage, 150 Hz pulse repetition rate and 5 mm electrode gap distance.