Volume Diffuse Dielectric Barrier Discharge Plasma Produced by Nanosecond High Voltage Pulse in Airflow*

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Abstract Volume diffuse dielectric barrier discharge (DBD) plasma is produced in subsonic airflow by nanosecond high-voltage pulse power supply with a plate-to-plate discharge cell at 6 mm air gap length. The discharge images, optical emission spectra (OES), the applied voltage and current waveforms of the discharge at the changed airflow rates are obtained. When airflow rate is increased, the transition of the discharge mode and the variations of discharge intensity, breakdown characteristics and the temperature of the discharge plasma are investigated. The results show that the discharge becomes more diffuse, discharge intensity is decreased accompanied by the increased breakdown voltage and time lag, and the temperature of the discharge plasma reduces when airflow of small velocity is introduced into the discharge gap. These phenomena are because that the airflow changes the spatial distribution of the heat and the space charge in the discharge gap.

Keywords: diffuse DBD, OES, airflow, atmospheric pressure, nanosecond pulse

PACS: 52.50.−b

DOI: 10.1088/1009-0630/18/5/13

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

1 Introduction

As a popular approach for generating atmospheric pressure low-temperature plasmas, dielectric barrier discharges (DBDs) have obtained more and more attentions [1−6]. In recent years, it has been used in many industrial fields such as thin film deposition [7,8], material surface treatment [9,10], bio decontamination [11−14] and ozone generation [15]. Considerable efforts have been made to study this kind of discharge driven by AC and pulsed power supply [1,2]. Although the uniformity of the discharge plasma is important for many applications, the atmospheric pressure DBDs present generally as self-organized patterns or random filaments, which will lead to some serious issues such as a non-uniform energy distribution and gas heating by the intense discharges in the random microdischarge channel. So it has become a main topic to generate a uniform high pressure DBD.

In the last several decades, many approaches have been introduced to produce uniform DBD, for example, making use of an appropriate working gas, the complicated electrode configuration and arrangement, and a short pulse power supply. However, because of the concerned energy and material cost and the large area requirement in the applications of homogeneous DBDs in many areas, using special working gas or an electrode configuration cannot solve the issue entirely. The discharges excited by nanosecond high-voltage pulses with fast rising front have gained more attentions [16,17]. In the discharge, most electrical energy consumed by the discharge is used to accelerate electrons rather than heating the heavy particles [18], therefore, compared to the conventional AC discharge, the nanosecond pulsed discharges display many superiorities, such as more uniform discharge, higher energy efficiency and lower plasma temperature [19,20]. It has been reported that, in the researches [21,22], when the duration of the discharge current pulse is shorter than the characteristic time of the discharge instability that causes the glow-to-arc transition (GAT), the discharge will present as glow discharge even when the current density is higher than the threshold for GAT.

Using a sphere-plane configuration, Ayan et al. [4,23] studied a uniform nanosecond pulsed DBD and they have utilized it in material surface treatment. Using a unipolar pulse power supply, Shao et al. [3,24] developed a uniform DBD and pointed out that the discharge gap length, the dielectric and the applied pulse repetition frequency (PRF) play an important

*supported by National Natural Science Foundation of China (No. 51437002)
role in influencing the discharge uniformity. Using needle-plate electrode configurations, Wang et al. [25,26] gained a diffuse DBD plasma by bipolar nanosecond high-voltage pulses. Using the nanosecond repetitively pulsed method, Pai et al. [27] generated an atmospheric pressure diffuse non-thermal plasma in preheated air (300 K to 1000 K) and found that the diffuse plasma discharge begins on an cathode-directed streamer, followed by a return wave of potential distribution.

In this work, large volume diffuse DBD plasma is generated by a nanosecond high-voltage pulse with a rise time of about 40 ns and duration of about 200 ns in airflow. The discharge characteristics are investigated systematically, and the effects of the airflow rate on the discharge are also investigated by contrasting the discharge images, electrical behavior and the OES of the discharge plasma at different airflow rates.

2 Experimental setup and measurement

Fig. 1 shows the schematic of the experimental setup. It is composed of a DBD actuator, a nanosecond pulse power supply, an airflow system, and a detection system. Two parallel placed rectangular metal electrodes serve as the anode and cathode, respectively. Both the two electrodes have the same area of 100 mm × 40 mm and are covered by mica plates served as dielectric barrier layers. The air gap length is fixed at 6 mm in this work. An adjustable water resistance parallel to the discharge cell is used to reduce the interference of the reflected wave to the electrical signals. The generator (ИСТОЧНИК ПИТАНИЯ500Вτ) was made in the institute of high voltage in Tomsk University of Technology of Russia and the average power of which is about 500 W. It can produce nanosecond high-voltage pulses with about 200 ns duration at half maximum, 40 ns rising time and 35 kV peak voltages. The PRF of the generator can be adjusted at the fixed values of 100 Hz, 300 Hz, 600 Hz, 1000 Hz, 1200 Hz and the voltage waveforms at different PRFs show good reproducibility. Airflows with velocities from 0 m/s to 50 m/s can be produced by a self-designed wind tunnel.

In detection system, a Tektronix P6015A high-voltage probe and a Tektronix TCP0150 current probe are used to measure the applied voltage and the total current, respectively. And the signals are recorded by a Tektronix DPO4104 digitalized oscilloscope (1.0 GHz 5 GS/s). A Nikon D3200 digital camera is employed to take the single-pulse discharge images used for evaluating the discharge uniformity with 1/1250 s exposure time at 1200 Hz PRF. An Acton 2500i grating monochromator with 2400 lines mm⁻¹ grating groove and 200 nm glancing wavelength is hired to collect the optical emission spectra (OES) of the plasma. And by using a pitot tube (testo512 200hPa), the airflow rate is measured at the upstream of the discharge volume.

3 Results and discussion

3.1 The visualization of the nanosecond pulsed DBD in airflow

Fig. 2 shows a series of single-pulse discharge images at different airflow rates. The exposure time is 1/1250 s. When the discharge is generated in open air without any gas flow, the discharge presents as a bunch of parallel filaments distributed in the discharge gap with a certain interval distance between one filament and the neighbors, as shown in Fig. 2. When the airflow (from left to right) of small velocity (less than 10 m/s) is introduced, the discharge transforms from filamentary discharge to diffuse mode gradually with the increased airflow rate. And the discharge presents completely as diffuse discharge when the airflow of higher velocity (higher than 10 m/s) is introduced.

![Image](image_url)

Fig. 2 Single-pulse discharge images of discharges at different airflow rates with the exposure time of 1/1250 s (the airflow paralleled to the electrodes passes through the discharge gap from left to right)

We think that the variation of the spatial distribution of the heat and the space charge at the beginning of the voltage pulse is the key reason for the discharge mode transition, and airflow will affect the distribution. For a filamentary discharge in the ambient air, there will be more space charges in the positions of discharge channels than in the neighborhoods when the next pulse arrives, and the space charge is favorable for the development of the next discharge, the reason is that more seed electrons will be produced by the penning ionization caused by the collision between metastable particles and nitrogen molecules. Meanwhile, more heat is
produced in the filament channel than in the neighborhoods due to the intense discharge, which leads to the reduction of the particle density in the channel positions. This case will maintain for a long time before the space charges are recombined and the heat dissipates. Therefore, the discharge has a positive feedback in these positions, in other words, the discharge will keep in filamentary mode. When airflow is introduced, the spatial distribution of the space charge and the heat will become uniform more sooner. On one hand, the same particle density is gain in the entire gap, which leads to an identical reduced electric field; on the other hand, the seed electrons will distribute homogeneously in the gap due to the space charge being uniform. In this case, the diffuse discharge is generated.

### 3.2 The electric characteristic of the nanosecond pulsed DBD

Fig. 3 shows the typical curves of the applied voltage and total current at 35 kV pulse peak voltage, 1200 Hz PRF, 50 m/s airflow rate and 6 mm air gap. We can see that discharge is excited primarily at the rising edge of voltage pulse. An abrupt voltage drop can be observed and a discharge current pulse is formed as the gas is broken down. The main reason of the voltage drop is that the output compensation of the pulse supply is low. The first current peak is responsible for the charging of the parasitic capacitance and the current peak at about 60 ns is for the discharge. And the duration of a single discharge manifested by the full width at half maximum (FWHM) of the discharge current peak is about $10^{-7}$ s.

![Fig.3](image)

Fig. 3 Typical waveforms of the applied voltage and total current of the nanosecond pulsed DBD at 35 kV pulse peak voltage, 1200 Hz PRF, 50 m/s airflow rate and 6 mm air gap

Fig. 4 shows the variation of the discharge intensity with the increasing airflow rate. The discharge current reduces rapidly from about 57 A to 37 A as the airflow rate increases from 0 m/s to 10 m/s, and then increases slowly to about 45 A when the airflow rate is further increased to 50 m/s. The result indicates that the discharge intensity is decreased due to the reduction in the number of microdischarge channels when the discharge transforms from filamentary to diffuse mode, and the airflow will promote the diffuse discharge slightly when the discharge conducts in diffuse mode.

![Fig.4](image)

Fig. 4 Effect of airflow rate on the peak value of the discharge current of the nanosecond pulsed DBD at 35 kV pulse peak voltage, 1200 Hz PRF, and 6 mm air gap length

For studying the impact of the airflow on the breakdown characteristic of the nanosecond pulsed DBD, the breakdown voltage and breakdown time lag versus the airflow rate are presented in Fig. 5. The little voltage drop at the rising edge, which can be seen from Fig. 3, indicates the occurrence of the breakdown, because that the insufficient instantaneous output power of the power supply will result in voltage collapsing. And the observational breakdown time lag is defined by Levinson and Kunhardt as the time interval between the beginning of the voltage pulse and the abrupt drop. From Fig. 5 we know that the breakdown voltage and the time lag have the same trends with the increasing airflow rate. Both the breakdown voltage and the time lag increase sharply when airflow rate is increased to about 10 m/s and then decrease slowly when the airflow rate is further increased to 50 m/s. So it can be concluded that the excitation of the discharge becomes difficult when the airflow with small velocity is introduced into the gap, while the airflow with a higher speed will promote the discharge slightly. The significant increase in breakdown voltage and time lag is attributed to the variation of the spatial distribution of the heat and space charge. For the filamentary discharge, the discharge channels, where the previous breakdown occurs, are the regions of lower neutral particle density and higher space charge density due to the intense discharge excited by the previous voltage pulse. However, the introduction of the airflow makes the heat and the space charge density in these positions reduced, i.e. the airflow makes the distribution of the heat and the space charge more uniform. Therefore, it is more difficult to excite discharge in an airflow than in quiescent air.

![Fig.5](image)

Fig. 5 The breakdown voltage and time lag of the nanosecond pulsed DBD as functions of the airflow rate at 35 kV pulse peak voltage, 1200 Hz PRF, and 6 mm air gap length
3.3 The gas temperature of the nanosecond pulsed DBD

Fig. 6 shows the OES produced by the nanosecond pulsed DBD at 35 kV pulse peak voltage, 1200 Hz PRF and 20 m/s airflow rate. The emission spectra are mainly composed of the first negative bands of \( \text{N}_2^+(B^2 \Sigma_u^+ \rightarrow X^2 \Sigma_g^+) \) and the second positive bands of \( \text{N}_2(C^3 \Pi_u \rightarrow B^3 \Pi_g) \). The effects of the airflow rate on the emission intensities of \( \text{N}_2(C^3 \Pi_u \rightarrow B^3 \Pi_g, 0-0) \) and \( \text{N}_2(C^3 \Pi_u \rightarrow B^3 \Pi_g, 0-2) \) are shown in Fig. 7. It can be seen that the peak values of \( \text{N}_2(C^3 \Pi_u \rightarrow B^3 \Pi_g, 0-0) \) and \( \text{N}_2(C^3 \Pi_u \rightarrow B^3 \Pi_g, 0-2) \) reduce quickly when the airflow rate is increased to about 10 m/s, and then keep almost constant until the airflow rate is increased to 50 m/s. It is indicated that the effects of the airflow rate on the emission spectra are the same as on the discharge current. The effects can be explained by the discharge becoming more diffuse, which results in a reduction in the number of the filament channel, thereby reducing the ionization degree in the discharge gap.

At atmospheric pressure, the dynamic equilibrium between the rotational motion of \( \text{N}_2^+ \) and the translational motion of \( \text{O}_2 \) and \( \text{N}_2 \) is easily achieved due to the frequent collisions of the heavy particles and the small energy gap of rotational levels. Therefore, the plasma temperature can be expressed by the rotational temperature of \( \text{N}_2^+ \). Using the software Lifbase, we determine the rotational temperature through comparing the OES of the first negative bands of \( \text{N}_2^+(B^2 \Sigma_u^+ \rightarrow X^2 \Sigma_g^+) \) and the best fitted spectra. Fig. 8 shows the experimentally measured spectra at 35 kV pulse peak voltage, 1200 Hz PRF and 20 m/s airflow rate and the simulated spectra with 473 K rotational temperature. We can see that the simulated spectra fit the experimental spectra well. So the plasma temperature at this experimental condition is equal to 473 K.

The dependence of the gas temperature of the nanosecond pulsed DBD plasma on airflow rate is shown in Fig. 9. It can be seen that the gas temperature is about 502 K when the discharge is excited in quiescent air and it decreases gradually to about 470 K as the airflow rate increasing gradually to 50 m/s. The decrease of the gas temperature can be explained from two aspects: one is that the measured value in filamentary discharge reflects the gas temperature in the brighter discharge channel, which is higher than the surrounding temperature; another is that the airflow takes part of the heat away from the discharge gap, which reduces the accumulation of the heat in the gap.

For the volume diffuse nanosecond pulsed DBD, the low gas temperature may be attributed to two reasons: one is that the duty cycle of the nanosecond pulse power supply is very low; another is that more energy input by the power supply is delivered to the energetic electrons instead of gas heating. Also, it is indicated that this kind of discharge plasma has promising application potential in many industrial fields, especially for the treatment of the heat-sensitive materials.
4 Conclusion

Volume diffuse DBD plasma is produced in subsonic airflow by employing nanosecond high voltage pulses on a plate-to-plate discharge cell at air gap length of 6 mm. The discharge images, electric characteristics and the optical emission spectra (OES) under different experimental conditions are obtained. When airflow rate is increased, the transition of the discharge mode and the variations of the discharge intensity, breakdown characteristics and the temperature of the discharge plasma are investigated. It is found that the discharge transforms from filamentary discharge to diffuse mode, discharge intensity is decreased accompanied by the increased breakdown voltage and time lag, and the gas temperature of the discharge plasma reduces when the airflow of small velocities is introduced. These can be explained by the variation of the spatial distribution of the heat and the space charge in the discharge gap caused by the introduction of the airflow. The experimental diffuse DBD plasma has a promising application potential in many industrial fields for the large area plasma with the good uniformity and low gas temperature.

References


(Manuscript received 9 September 2015)
(Manuscript accepted 13 October 2015)
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