# Investigation on the Micro-Discharge Characteristics of Dielectric Barrier Discharge in a Needle-Plate Geometry*

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**Abstract** In this study, a dielectric barrier discharge device with needle-plate electrodes was used to investigate the characteristics of the micro-discharge in argon at one atmospheric pressure by an optical method. The results show that there are two discharge modes in the dielectric barrier discharge, namely corona mode and filamentary mode. The corona discharge only occurs in the vicinity of the needle tip when the applied voltage is very low. However, the filamentary discharge mode can occur, and micro-discharge bridges the two electrodes when the applied voltage reaches a certain value. The extended area of micro-discharge on the dielectric plate becomes larger with the increase in applied voltage or decrease in gas pressure. The variance of the light emission waveforms is studied as a function of the applied voltage. Results show that very narrow discharge pulse only appears at the negative half cycle of the applied voltage in the corona discharge mode. However, broad hump (about several microseconds) can be discerned at both the negative half cycle and the positive half cycle for a high voltage in the filamentary mode. Furthermore, the inception voltage decreases and the width of the discharge hump increases with the increase in applied voltage. These experimental phenomena can be explained qualitatively by analyzing the discharge mechanism.

**Keywords:** dielectric barrier discharge, needle-plate geometry, optical method

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## 1 Introduction

Gas discharge at atmospheric pressure is extensively applied because it can be easily used for batch processing and without vacuum condition [1~4]. Atmospheric pressure plasmas can be generated by corona discharge, arc discharge, dielectric barrier discharge, etc. In arc discharge, thermal plasma is generated, which are mainly applied in metallurgy, cutting and spraying. In corona discharge and dielectric barrier discharge, nonthermal plasma is generated. The plasma generated in corona discharge is confined in the vicinity of the electrode, and hence with limited application. Among various modes of discharge, dielectric barrier discharge is promising to generate plasmas and widely applied in material modification, UV and VUV generation, environmental protection (such as exhaust gas processing), disinfection of medical apparatus, plasma display panels and propulsion of small satellites [5~7].

Dielectric barrier discharge is a kind of non-equilibrium AC gas discharge, in which at least one of the two electrodes is covered by a dielectric layer. The discharge can only be sustained in AC current because of the existence of a dielectric layer. Under most circumstances, micro-discharge filaments are distributed on the electrode stochastically at high pressure [8]. These filaments can be self-organized under proper conditions where a pattern formation can be observed [9]. Experimental results show that no micro-discharge filament can be discerned and uniform discharge (called atmospheric pressure glow discharge) can take place in the gas gap for some special species such as helium, neon and nitrogen [10,11]. Obviously, investigations into micro-discharge are important for pattern formation dynamics and realization of atmospheric pressure glow discharge. In recent years, close attention has been paid to the characteristics of micro-discharge in the dielectric barrier discharge between two parallel-plate electrodes [9,10,12]. Both experimental and theoretical investigations about this kind of discharge configurations are conducted extensively. However, there have been relatively few studies about micro-discharge in a nonuniform field such as in needle-plate electrode configurations.

In this study, a dielectric barrier discharge device with needle-plate electrodes is used to investigate the characteristics of the micro-discharge in argon at one atmospheric pressure by means of an optical method. The discharge mechanism is qualitatively examined by analyzing the waveforms of the applied voltage and the light emission signals.

## 2 Experimental setup

A schematic drawing of the experimental setup is shown in Fig. 1. The plasma is generated between a needle electrode and a water electrode covered with a

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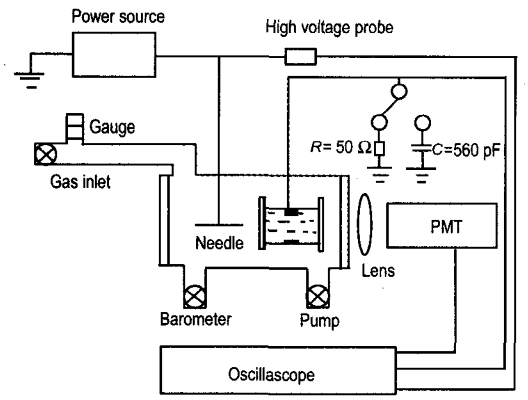
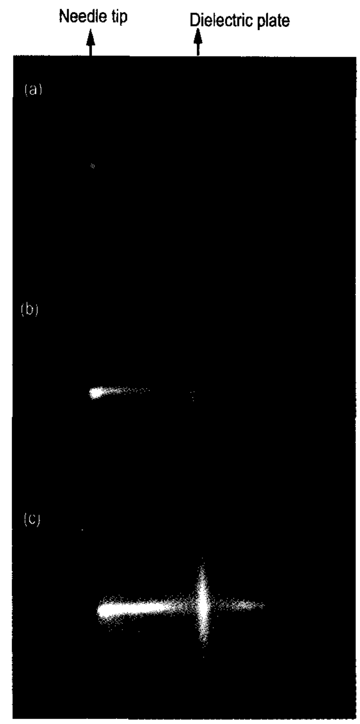



**Fig.1** Schematic diagram of the experimental setup

layer of quartz glass with a thickness of 1.5 mm. The tungsten needle is with a tip radius of 220 μm. A cylindrical glass container filled with tap water is used as the water electrode with a diameter of 75 mm. Both ends of the glass container are sealed by quartz glass. A metallic ring is immersed in the water container and grounded. The needle is fixed by a piece of rubber and protrudes from the holder by 2 cm. The total length of the needle is about 5 cm. The gas gap is 2.5 mm from the needle tip to the quartz glass. The discharge device is placed in a Perspex vacuum vessel. The vessel is pumped by a mechanic pump to its limit and then filled up with argon (99.99%) as working gas. The gas pressure is kept at one atmosphere. The blunt end of the needle is connected to the high voltage output of a power source, which can generate a sinusoidal voltage with a peak value of 10 kV and a frequency of 55 kHz. The applied voltage can be measured by a high voltage probe (Tektronix P6015A, 1000X) and recorded with an oscilloscope (Tektronix DPO4054). To record the discharge images, a digital camera (Canon Powershot G1: 3.24 mega pixels) is used with an exposure time of 8 ms in our experiments. Light emission from the discharge is detected by a photomultiplier tube (RCA7265) and recorded by the oscilloscope.

# 3 Results and discussion

By increasing the voltage of the power source, corona discharges appear at the vicinity of the needle tip at a peek voltage ($U_p$) of 1.4 kV. The light emission from the discharge is very weak, as shown in Fig. 2(a). With the increase in applied voltage the light emission gets stronger and the diameter of the discharge increases slightly. In the corona discharge mode the discharge is almost spherical. When the applied voltage reaches 4.1 kV the discharge becomes a plasma channel that bridges two electrodes. This plasma channel can be called micro-discharge filament. From Fig. 2(b), it can be observed that the plasma channel has a horn shape with the strongest emission at the vicinity of the needle tip. The discharges almost keep the cylindrical plasma channel from the needle tip to the middle of the gas gap, but diverge from the cylindrical channel in the neighborhood of the dielectric layer. The emission on the right of the dielectric comes from the reflection of the quartz glass. With a further increase in the applied voltage, the emission from the discharges becomes intense. Fig. 2(c) shows an image of the micro-discharge with $U_p$ at 4.8 kV.




(a)1.4 kV, (b) 4.1 kV, (c) 4.8 kV

**Fig.2** Discharge images under different voltages

From Fig. 2, it can also be found that the diameter of discharge increases with the increase in applied voltage, observed through the water electrode. Fig. 3 shows the discharge diameter as a function of voltage for different pressures. It is clearly shown that the diameter of the discharge increases with the increase in applied voltage and the same pressure. It decreases with the increase in gas pressure and the same voltage. Corona discharge can only appear when the applied voltage is slightly above the breakdown voltage, and then change to filament discharge with a slight increase in voltage at low pressure. However, the discharge keeps in the corona mode over a wider range of the applied voltage at atmospheric pressure. Under the corona discharge mode, the average free path of electrons increases with the decrease in pressure. Therefore, the electrons gain more energy from the electric field under a lower pressure. Consequently, the corona discharge can be sustained at a broader area with the decrease in pressure. Similarly, the critical voltage decreases for the whole gas gap breakdown with the decrease in pressure. This is consistent with the experimental results shown in Fig. 3.

Under the filament discharge mode, charges move toward the dielectric and accumulate on the dielectric

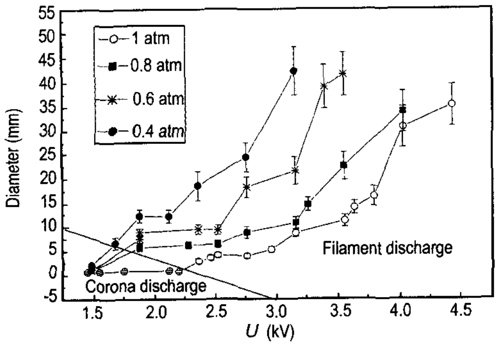



**Fig.3** Discharge diameter on the water electrode as a function of voltage for different pressures

layer to form wall charges. These wall charges will repel the forthcoming charges moving toward the dielectric layer. Therefore, the drift velocity is slow at the vicinity of the dielectric layer compared to that at the needle tip. The discharge tends to converge because of a pinch effect resulting from the electromagnetic attraction between the moving charges. However, diffusion will cause the discharge to diverge and the repelling force from the wall charges will also cause the discharge to diverge. Consequently, the discharge is a channel near the needle tip, while it is in a horn shape at the vicinity of the dielectric layer. More wall charges are accumulated on the dielectric layer with the increase in applied voltage. The repulsion gets stronger with the increase in applied voltage. As a result, the discharge diffusion diameter increases with the increase in applied voltage. With the decrease in gas pressure, more wall charges are needed to quench the breakdown because of a lower electric field at a lower pressure. Based on the same reason, the discharge diffusion diameter increases with the decrease in gas pressure.

Fig. 4 shows the waveforms of the applied voltage and light emission signal in the corona discharge mode. It can be found that there is only one discharge pulse for one cycle of the applied voltage and the discharge pulse with a duration of about 0.1 $\mu s$ always appears at the negative half cycle. In the corona discharge mode, the high-field region only exists at the vicinity of the needle tip. When the applied electric field is above a critical value for breakdown, electrons emitted from the needle tip would gain energy from the electric filed to

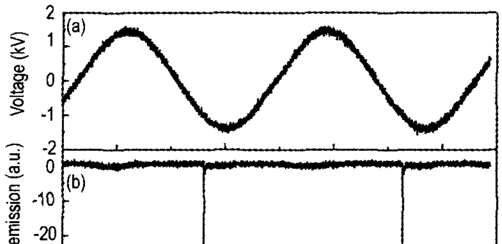



**Fig.4** Waveforms of (a) the applied voltage and (b) the light emission in the corona discharge mode

ionize argon atoms. The number of electrons increases due to the avalanche process. The drift velocity of electrons is very low when the electrons move to the low-field region. Therefore, the needle tip with negative potential is covered by electron cloud. Because of the shielding effect of this electron cloud, the electric field near the needle tip is lowered and the discharge is quenched. As a result, the emission waveform shows a pulse. Only discharge emission at the negative half cycle is observed because the breakdown field with negative potential is lower than that with positive potential.

Fig. 5 shows the waveforms of the applied voltage and the light emission in the filamentary mode. It is shown that the discharge is composed of a pulse with a duration of about 1 $\mu s$ and a hump (continuous discharge profile) with a duration of about 6 $\mu s$ for the positive half cycle of the applied voltage and the negative one, respectively. The different waveforms may result from different discharge mechanisms for the two different half cycles. Assume that the discharge hump results from the formation of a cathode fall region. During the discharge, an electron avalanche develops from the instantaneous cathode (needle electrode) to the instantaneous anode (water electrode), and most positive ions are generated near the instantaneous anode. They will slowly move towards the instantaneous cathode (needle electrode) and collide with the cathode to generate secondary electrons. When most ions reach the vicinity of the cathode, the net electric field is affected by these space charges, and the voltage is mostly applied on the gap between the cathode and the layer of space charges. This region is called the cathode fall region. When the cathode fall region is formed, ions have enough energy to generate secondary electrons after they have been accelerated in the cathode fall region and electrons can also have enough energy to cause the avalanche in the cathode fall region even if the voltage is not too high. So the voltage to maintain the discharge is lowered significantly compared to Townsend discharge. Therefore, there is a hump lasting until the applied voltage decreases to a certain value.

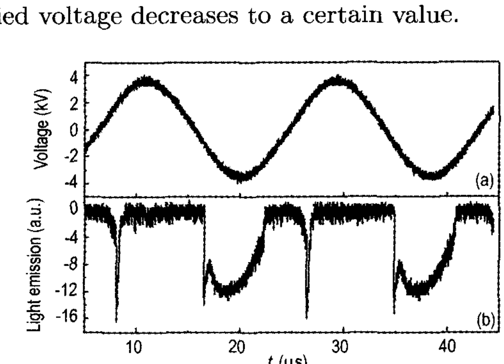



**Fig.5** Waveforms of (a) the applied voltage and (b) the light emission in the filamentary mode at low voltage

This pulsed discharge at the positive half cycle results from the Townsend breakdown mechanism where no cathode fall region is formed. Without the formation of a cathode fall region, the voltage to sustain the discharge is fairly high and the discharge quenches quickly because of the accumulation of wall charges. Therefore, the discharge pulse can only be observed at the positive half cycle. The cathode fall region is first formed in the negative half cycle probably because the ions converge towards the needle electrode due to the electrode configuration. The higher the ion density is, the easier the cathode fall region is to form.

With a further increase in the applied voltage, a discharge hump can appear in each half cycle, as shown in Fig. 6. The appearance of hump discharge in both half cycles indicates that the cathode fall region can be formed even if the water electrode is the instantaneous cathode. The formation of the cathode fall region in the positive half cycle may result from the ion accumulation during the previous Townsend discharge pulse.

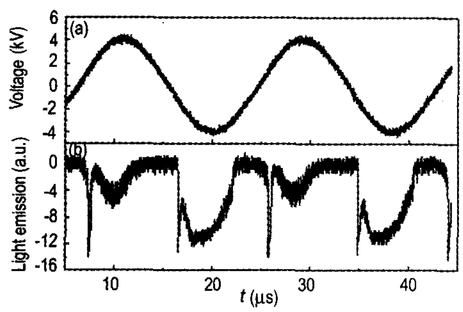



**Fig.6** Waveforms of (a) the applied voltage and (b) the light emission at high voltage

With the further increase in applied voltage, the inception voltage decreases. That is to say, the breakdown moments for both half cycles are in advance. The discharge can be ignited at the falling edge of the applied voltage for a sufficiently high voltage, as shown in Fig. 7. The wall charges accumulated on the dielectric increase with the increase in voltage. The electric field of the wall charges will help the breakdown of the forthcoming half cycle. Therefore, the applied electric field for the breakdown decreases with the increase in voltage.

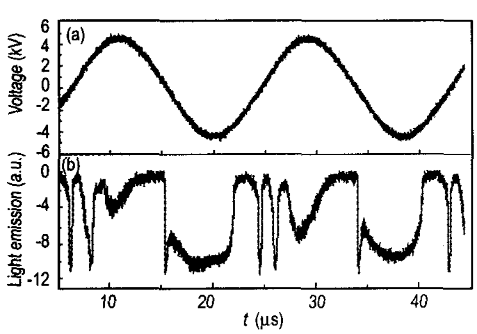



**Fig.7** Waveforms of (a) the applied voltage and (b) the light emission when the breakdown occurs at the falling edge of the voltage

# 4 Conclusion

The characteristics of a dielectric barrier discharge in argon with needle-plate electrodes was investigated at one atmospheric pressure by an optical method. Experimental results show that there are two discharge modes in the dielectric barrier discharge, namely the corona discharge mode and filamentary mode. The corona discharge only occurs in the vicinity of the needle tip for a very low applied voltage. However, the filamentary discharge mode can occur, and micro-discharge bridges the two electrodes, for the applied voltage reaching a certain value. The extended area of micro-discharge on the dielectric plate becomes larger with the increase in applied voltage or the decrease in gas pressure. The variance of light emission waveforms as a function of the applied voltage is studied. Results show that in the corona discharge mode a very narrow discharge pulse only appears at the negative half cycle of the applied voltage. However in the filamentary mode a broad hump can be discerned at both the negative half cycle and the positive half cycle for a high voltage. Furthermore, the inception voltage decreases and the width of the discharge hump increases with the increase in applied voltage. These experimental phenomena have been assessed qualitatively by analyzing the discharge mechanism.

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