Characterization of millimeter magnitude atmospheric pressure glow discharge in pin-to-plane dielectric barrier discharge

Z Yu¹, Z T Zhang¹²*, S J Xu², J Yao², Q X Yu², Y J Li², J S Zhao¹

¹ Institute of Marine Engineering, Dalian Maritime University, Dalian 116026, China
² Department of Physics, Dalian Maritime University, Dalian 116026, China

E-mail: newzhangzhitao@163.com

Abstract. Discharge mode in pin-to-plane dielectric barrier discharge at atmospheric pressure was investigated by means of the electrical measurement, the photo-electricity and the fast macro photography. The discharge was operated in atmospheric air. Streamer and glow discharge were generated in the positive half-period and negative half-period of discharge respectively with a 10 kHz AC power supply when the applied voltage reached a high value. The subject of this paper is the study of the characterization of the glow discharge. It was found that the glow discharge have the hierarchical structure, although the discharge gap is small (only 0.9 mm). The positive column is shortened as the distance of discharge gap decreases, but the dimensions of other discharge area do not change. The discharge current waveform illustrates that the positive half-period discharge current is very short, which is streamer current waveform, and the negative half-period one is longer, which is glow discharge current waveform. The photo-electricity signal waveform corresponds with discharge current waveform. Two main glow discharge generating reasons are proposed in this paper. One is a sufficient number of space charge produced in the very uneven electric field around needle electrode; the other is the effective secondary electron emission process on the exposed needle electrode.

1. Introduction

Dielectric barrier discharge (DBD) is widely used in ozone generation, material surface treatment, pollution abatement, UV light source, plasma display technology, etc [1, 2]. Generally, there are two main discharge modes in the DBD system, streamer and homogeneous mode. In atmospheric air, streamer mode is common mode, due to the higher density of gas and electronegative gas such as oxygen, water vapour, etc. Since the 1980s, homogeneous mode became a new research hotspot because of the industrial application needs. In 1988 [3], the homogeneous mode in atmospheric pressure helium was first found by Okazaki in Japan. The homogeneous mode includes Townsend discharge and glow discharge. In the Townsend mode, the strongest luminous layer is observed close to the anode, because the electric field is almost uniformly distributed along the gap. In glow discharge,
on the contrary, the strongest luminous layer is closed to the cathode, because the space charge around
the cathode is distorted the electric field [4]. In 2003 [5-7], Radu in Canada realized the glow
discharge with the pin-to-plane and cylinder-to-plane DBD system, but the discharge gas only focused
on noble gas. And then, some researchers also realized the homogeneous discharge with some special
methods and electrode form, such as pre-ionization of spark, Mesh electrode, etc [8-11]. But the
discharge in the most of the research results does not have the hierarchical structure that like typical
low pressure glow discharge, therefore some researchers only regard it as Townsend discharge [12].
Streamer is often adopted in the industrial application. Research shows that the productivity of active
particles in homogeneous discharge is higher than that in streamer [13]. So, the efficiency of chemical
reaction will be improved if the homogeneous mode introduces into discharge system.

In 1938 [14], G W Trichel reported a negative corona discharge (named Trichel pulses) with only
few micro amps of current, occurred in the extremely uneven electric field around the cathode. When
the electric field rises, Trichel pulses discharge transforms to glow discharge. This glow discharge has
hierarchical structure like glow discharge in low pressure, albeit on a very small scale. In the pin-to-
plane electrode without dielectric layer, because the discharge current increases rapidly, the glow
discharge is not stable and transforms to arc easily. But if there is a dielectric layer between pin and
plane electrode (i.e. pin-to-plane DBD), on the one hand, extremely uneven electric field forms around
the cathode, on the other hand, discharge current does not increase too fast, due to the existence of the
dielectric layers. However, needle electrode won't always keep negative potential because of the AC
power source, the streamer will happen when the needle electrode is positive potential. So, two kinds
of modes (streamer and glow) happen alternately in pin-to-plane DBD system.

In this paper, the glow discharge in the two modes is the main research object. The detail of glow
discharge morphology is acquired by the CCD camera with macro lens. The mechanism is expounded
qualitatively at last.

2. Experiment setup and method

The experiment setup is schematically shown in figure 1. The discharges were generated between
exposed needle electrode and plane electrode covered by rectangular Al₂O₃ dielectric layer with
thickness 0.47 mm. An adjustable high voltage power source with amplitude from 0 to 10 kV and
frequency 10 kHz is connected to the needle electrode, the plane electrode is grounded. The pin-to-
plane DBD reactor was placed in a chamber which is connected to a rotary pump. In our experiments,
only air without additional gas is used.

![Figure 1. Experiment setup.](image-url)
The light emission images from the discharge are recorded by a CCD camera (CoolSNAP EZ) which is mounted macro lens (2 ×, SE-16SM), with the exposure time 1 μs and spectrum response from 300 to 1000 nm. The voltage applied to the needle electrode is measured by a high voltage probe (HV-P60, Japan). The discharge current is measured by a 51.1 Ω non-inductance resistor (R) placed between plane electrode and ground. Photoelectric signal acquired via a PMT (SENS-TECH DM0047C, English). The voltage, current waveform and photoelectric signal are recorded by a digital oscilloscope (Tektronix TDS3032B, America).

3. Experiment results and discussions

Figure 2 shows the discharge character of pin-to-plane DBD system in which the applied voltage is 6 kV, the discharge gap is 0.9 mm, and the thickness of dielectric layer is 0.47 mm. The applied voltage waveform and the discharge current waveform without displacement current are shown in figure 2(a) and figure 2(b) respectively. It can be seen that there are numerous short current pulses in the positive half-period of the discharge current waveform and only one wide current pulse in the negative half-period. Figure 2(c) shows the photoelectric signal waveform which has the characteristics like the discharge current waveform. So, it can be sure that there are two kinds of discharge modes generated alternately. Figure 2(e) and figure 2(f) are the discharge morphology acquired by CCD camera in the moment of figure 2(b)I and figure 2(b)II respectively. Two kinds of discharge mode is clearly distinguished in this two pictures. Figure 2(e) shows a typical streamer mode, but in the figure 2(f) there is a distinct different discharge mode which can be characterized by hierarchical structure orderly consisted of negative glow, Faraday dark space, positive column, Anode glow, and cathode dark space. We call it micro-glow discharge momentarily, because it is only less than a millimeter.

![Figure 2](image)

**Figure 2.** The waveform of applied voltage (a), discharge current (b) and photoelectric signal (c), the images of streamer (e) and micro-glow discharge (f).
In the experiment, only when the applied voltage reach to a certain value $U_c$, the micro-glow discharge is generated in the negative half-period of discharge current waveform. If the applied voltage is less than $U_c$, the discharge is only corona or Trichel pulse in the negative half-period. But in this paper, we focus on micro-glow discharge, rather than discuss what discharge mode it is, corona or Trichel pulse. The waveform of photoelectric signal with increase of applied voltage is shown in figure 3. The photoelectric signal is all short pulses in positive and negative periods, as shown in figure 3(a). When the applied voltage reach to 4 kV (figure 3(b)), a wide and week photoelectric signal appears in the negative half-period, that is the photoelectric signal of micro-glow discharge. And then, the photoelectric signal strengthens gradually with increase of applied voltage. In figure 3(b), (c), (d), moreover, there are some short pulses generated before the wide pulse of micro-glow discharge. These short pulses are corona or Trichel pulse. Owing to the AC power source, corona or Trichel pulse are generated before the applied voltage reach to $U_c$. Then, the transition from corona or Trichel pulse to micro-glow discharge is happened when the applied voltage is higher than $U_c$.

![Figure 3](image1.png)  
*Figure 3.* The waveform of photoelectric signal when the applied voltage is 3kV, 4kV, 5kV and 6kV.

![Figure 4](image2.png)  
*Figure 4.* The transition applied voltage of different discharge modes in different discharge gap.

So, the discharge modes change is observed clearly through the waveform of photoelectric signal. With the increase of the applied voltage, there are only streamers with different discharge strength in the positive half-period. But in negative half-period, the discharge mode is more complex. First, when the applied voltage is less than discharge ignition voltage $U_d$, there is no discharge in the discharge gap. Secondly, when the applied voltage is between $U_d$ and $U_c$, corona or Trichel pulse is generated. And then, the applied voltage is more than $U_c$, the transition from corona or Trichel pulse to micro-glow discharge is observed in the negative half-period. $U_d$ and $U_c$ are higher with the increase of discharge gap, as shown in the figure 4.
Figure 5 shows the images of micro-glow discharge with different gap of 1.2 mm, 0.9 mm, 0.6 mm and 0.3 mm, applied voltage 6 kV. It is noted that the size and strength of micro-glow discharge features is unchanged except positive column. Like the glow discharge in the low pressure, the positive column of the micro-glow discharge is shortening with the decrease of discharge gap, and disappearing when the discharge gap is reduced to 0.3 mm.

![Figure 5. Images of micro-glow discharge with the gap of 1.2 mm, 0.9 mm, 0.6 mm and 0.3 mm.](image)

The mechanism leading to micro-glow discharge is speculative at two points. First, there are enough space charges in the discharge gap. A lot of space charge, generated in the positive half-period, is not disappeared in the negative half-period. So, the cathode potential drop is formed between the space charge and needle cathode. Bright negative glow appear following the area of cathode potential drop. Secondly, secondary electron emission is efficient on the needle cathode. Strong electric field strength, formed around the needle cathode, is conducive to secondary electron emission.

4. Conclusions
In this paper, we have presented the micro-glow discharge in the pin-to-plane DBD device. The hierarchical structure of micro-glow discharge is clearly revealed by the CCD camera with the macro lens. Enough space charge and efficient secondary electron emission is two critical factors for generating of micro-glow discharge.

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