Study on the Morphology of the Streamer with Carbon Nanotube Electrode in Atmospheric Environment

Xin Liu*

School of Electronic Information and Electrical Engineering, Shanghai Jiao Tong University, Shanghai, China

*Corresponding author e-mail: lxzhisheng@sjtu.edu.cn

Abstract. The low temperature streamer at atmospheric pressure has good characteristics of pollutant removal, and the characteristics of the streamer are closely related to the discharge conditions, and the structure and material of the electrode also affect the characteristics of the streamer. In our work, the argon gas was discharged under different conditions and the morphology of streamer was shot by a high-speed camera, then the morphology of the streamer that generated by the carbon nanotube electrode was compared under the same conditions. The experimental results show that when the electrode is electroplated with carbon nanotubes, the light intensity and the diameter of the streamer will increase, and the morphology of the streamer that in the atmosphere will change regularly with the discharge conditions. The experiment proved that the morphology of the streamer will be influenced by the discharge conditions because of the electric and flow fields, and the carbon nanotube electrode will generate more intense streamer.

1. Introduction

Atmospheric pressure low-temperature plasma streamer produced by gas discharge in atmospheric environment, because it requires less equipment investments, and the temperature is low, and it can also produce a higher concentration of active particles and so on, so it can be applied in environmental engineering, material processing, biomedicine and other fields [1] [2] [3] [4]. In recent years, it has become an important study, Liu Yongjun et al used liquid glow discharge plasma to clean phenol-containing wastewater, they found that the concentration of phenol in solution decreased with the increase of discharge time, and after 180 min of treatment, the phenol in solution was removed by 95% [5]; Bing Sun studied the effect of pulsed streamer corona discharge on the removal rate of phenol in solution and the effect of various discharge parameters on the removal rate, he found that pulsed discharge can effectively remove organic pollutants from water, and organic matter can be reduced by 83% without oxygen bubbling, and the organic matter can be removed by 86% with aerobic bubbling [6]; Horikoshi et al used ultrasound and microwaves to produce plasma in water, and use it to remove perfluorooctanoic acid, the results showed that 59% of perfluorooctanoic acid could be removed after 90 s radiation when the microwave power was 220 W [7].

When plasma is used to treat wastewater, the effect is related to the concentration of the plasma, and different concentrations of plasma correspond to different morphological characteristics, so the morphology of plasma streamer is related to the contaminant removal effect, therefore, the study of the
relationship between the morphological of plasma streamer and discharge conditions is important. Pan Wenxia and other scholars have studied the changes of the length of the streamer under different gas flow or arc current, they found that the scale of the streamer changed regularly with the external parameters, and the length of the streamer increased significantly with the increase of gas flow or arc current [8]; Song peng et al. studied the ionization characteristics of dielectric barrier discharge under different electrode structures, they found that the intensity of the discharge of the streamer by the dentate electrode is larger and the discharge effect is remarkable, the intensity of the discharge of the cylindrical electrode is weak, but it is easy to form large area homogeneous plasma [9]. These studies show that there is a complex relationship between the morphology of streamer and some external parameters, such as the structure of electrode, voltage, frequency and gas flow rate. However, there are few researches on the plasma streamer of the nanometer material electrode, therefore, the main work of this paper is discharge argon with DBD under different discharge conditions, and the changes of the morphology of the streamer were observed by a high-speed camera, the streamer produced by carbon nanotube electrode was also studied, and the effects of carbon nanotubes on the streamer were studied by comparing with the electrode without carbon nanotubes.

2. Experimental and analytical methods

2.1. Electrophoresis deposition of carbon nanotubes

In this experiment, carbon nanotubes were deposited on the discharge electrode based on the principle of electrophoretic deposition, the discharge electrode is a stainless steel tube with a diameter of 8mm, the equipment for electrophoretic deposition is a discharge power and an electrophoretic tank, the concentration of carbon nanotubes in the aqueous dispersion was 8%, the distance between two electrodes was 1cm, the voltage and current were 15.5V and 0.1A, and the duration of the electrophoresis was 30min, then the product was dried at 60°C for 20min.

2.2. Dielectric barrier discharge in atmospheric environment

This experiment mainly relies on the principle of dielectric barrier discharge to discharge argon gas at atmospheric pressure, the experimental system structure diagram is shown as Figure 1.

![Image](image.png)

**Figure. 1** The diagram of the experimental system structure.

The discharge power used in the experiment is Trek power, the structure of the discharge chamber used in the experiment is a four-way quartz tube, in the discharge cavity, the longer quartz single tube is a 200mm long hollow cylinder, and the wall thickness of the quartz tube is 2.5mm, and the inner diameter is 100mm, the length of the short quartz single tube is 50mm, and the inner diameter is 6mm and the outer diameter is 10mm. The electrode was placed inside the quartz tube and extended through the shorter quartz tube channel, and another shorter quartz tube is then wound with a circular copper electrode, the distance between the two electrodes is 5cm. The density of argon used in the experiment is $\rho=1.7841\text{kg/m}^3$, the kinematic viscosity coefficient is $\mu=2.23\times10^{-5}\text{Kg}(\text{m s})$, $d=8\text{mm}$. According
to the Reynolds number: \( Re = \frac{\rho v d}{\mu} \), we can calculate that \( Re \) is less than 2300, the flow field is in laminar state. According to the fluid mechanics model, the boltzmann equation of streamer is shown as equation 1, \( f(t, \vec{r}, \vec{v}) \) is distribution function, \( e \) is unit charge, \( m_e \) is electron Mass, and \( E \) is the electric-field intensity. These parameters are related to electric and flow fields, so the discharge condition parameters set during the experiment are shown as Table 1

\[
\frac{\partial f(t, \vec{r}, \vec{v})}{\partial t} + v_e \cdot \nabla \cdot f(t, \vec{r}, \vec{v}) - \frac{e}{m_e} \vec{E} \cdot \nabla f(t, \vec{r}, \vec{v}) = C[f(t, \vec{r}, \vec{v})]
\]  

Table. 1 The parameter of discharge

| Number | Voltage | Current | Frequency | Gas flow |
|--------|---------|---------|-----------|----------|
| 1      | 15KV    | 3mA     | 1.1KHz    | 10L/min  |
| 2      | 15KV    | 3mA     | 1.5KHz    | 10L/min  |
| 3      | 15KV    | 3mA     | 2.0KHz    | 10L/min  |
| 4      | 15KV    | 3mA     | 1.5KHz    | 5L/min   |
| 5      | 15KV    | 3mA     | 1.5KHz    | 15L/min  |
| 6      | 14.6KV  | 3mA     | 1.5KHz    | 15L/min  |
| 7      | 13.3KV  | 3mA     | 1.5KHz    | 15L/min  |
| 8      | 11.6KV  | 3mA     | 1.5KHz    | 15L/min  |

2.3. The experiment of high-speed camera

After we obtain the streamer under each condition, a high-speed camera was used to shoot the streamer. The high-speed camera used in the experiment was ix cameras i-speed 7, the frame rate used was 3000 frames per second, the camera was kept in the same horizontal position with the discharge chamber during the shooting process, and the camera is 1.2m away from the discharge chamber, and the shooting time lasts for 1min.

3. Analysis and discussion of the results

3.1. The evolution of the streamer produced by electrode without CNT

When the streamer produced by the electrode without CNT, the image data obtained by the high-speed camera was shown as Figure 2. From the (1)-(3), it can be found that when the frequency was increased, the discharge area in the discharge space will expand and the light intensity of streamer will increase.

Figure. 2 The images of the streamer produced by the electrode without CNT under different conditions
Also increase. According to the researches of Li Qingquan, the equivalent capacitance between the discharge electrodes is only related to the electrode structure in the same voltage, and it won’t change with the frequency, and the initial voltage and extinction voltage remain unchanged, the voltage and the total charge are maintained during each half cycle of discharge, so the discharge power is proportional to the discharge frequency [10]. Therefore, the reason for this phenomenon is that the discharge power will increase with the increase of the discharge frequency. Therefore, the particle collision will be more intense, and the ionizing luminescence phenomenon will be enhanced during the discharge process [11].

From the (4)-(6) above, it can be found that when the gas flow rate was increased, the discharge area of streamer will gradually extend along the gas path, and the streamer was more stable and brighter, the following reaction will occur during this process as the equation 2.

\[
\text{Ar} + \text{e} \rightarrow \text{Ar}^{+} + 2\text{e}, \quad \text{Ar} + \text{e} \rightarrow \text{Ar}_{\text{m}} + \text{e}, \quad \text{Ar} + \text{e} \rightarrow \text{Ar}_{\text{r}} + \text{e}, \quad \text{Ar} + \text{e} \rightarrow \text{Ar}^{*} + \text{e}
\] (2)

The e represents the electron, the Ar\(^{+}\) represent the argon-ion, the Ar\(_{r}\) represent the Argon in resonance state, and the Ar\(_{m}\) represents the the argon atom in metastable, and the Ar\(^{*}\) represents the excited argon [12]. The initial discharge region of the gas occurs upstream of the streamer where the concentration of Ar is highest, therefore, more excited argon ions will be generated under the influence of external voltage, so it is easier to discharge than other areas. However, with the gradual increase of gas flow rate, Ar will move to the radial direction of the gas path, and the concentration of Ar in the remaining areas will be increased, because the concentration of excited argon ions increases, the collision becomes more violent. So the discharge phenomenon will be more violent, and the streamer will be more stable [11].

From the (7)-(10) above, it can be found that the light intensity of the streamer will be slightly enhanced when the voltage was increased, and the morphology of the streamer will be more regular, and more discharge filaments were produced. Because the power will be increased when voltage was raised and the other conditions were kept the same, finally, the breakdown voltage in the discharge chamber was decreased [11]. Therefore, when the voltage was increased, the streamer will be more regular and there will be more discharge filaments around it.

According to the experimental results above, when the conditions are changed under a certain rule, the morphology of the streamer also be in different states, this proved that the morphological evolution of streamer is determined by external conditions, and there is a certain regularity in this process.

3.2. The evolution of the streamer produced by carbon nanotube electrode
When the streamer produced by electrode without CNT, the SEM image of the electrode are shown as Figure 3. From the (a)-(b), it can be found that when the electrodes were deposited by the carbon

![Figure 3](image-url) (a) The SEM image of the electrode without CNT; (b) The SEM image of the carbon nanotube electrode
Nanotubes, there will be more accumulation of carbon nanotubes on the electrode surface compared to the electrode without CNT, and the carbon nanotubes distributed densely. The image data obtained by the high-speed camera was shown as Figure 4. From these images it can be found that the evolutional law of the streamer that obtained by carbon nanotube electrode is consistent with the previous evolution, but under the same discharge conditions, the carbon nanotube electrode produced a streamer with stronger light, and the diameter of the streamer is longer than the streamer produced by electrode without CNT. According to the researches of wang Yuhua, the reason for this phenomenon is that there is a one-dimensional nanostructure on the electrode, so the space charge has a positive feedback effect on the discharge process, and the process of the reduction of space charge on the surface of dielectric barrier layer may exist simultaneously [13], therefore, the photoionization process will be more intense, and the brightness and scale of the streamer will be increased.

Figure 4 The images of the streamer produced by the carbon nanotube electrode under different conditions

4. Summary
In this paper, the evolutional law of streamer generated by DBD discharge under different conditions is observed, the argon was discharged by DBD at atmospheric pressure, it is observed that the morphology of the streamer will change regularly with the changes of the discharge voltage, frequency and gas flow rate, we found that when the frequency was increased, the discharge area in the discharge space will be expanded, and the light intensity of the streamer will be increased; When the flow rate of the gas is increased, the discharge area will gradually extend along the gas path, the morphology of the streamer will become more stable and the brightness will be increased; When the voltage is increased, the light intensity of the streamer is increased and more discharge filaments are produced. We also found that when carbon nanotube electrodes were used for DBD discharge, the evolution law of the streamer will be the same as the streamer produced by the electrode without CNT, but the brightness and scale of the streamer will be enhanced. Therefore, when the carbon nanotube electrode is used for DBD discharge, we will get a stronger streamer, and a stronger streamer can be more efficient for sewage treatment and other work.
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