Study on the Generation Characteristics of Dielectric Barrier Discharge Plasmas on Water Surface

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Abstract A new contact glow discharge electrode on the surface of water was designed and employed in this study. Because of the strong field strength in the small air gap formed by the electrode and the water surface, glow discharge plasmas were generated and used to treat waste water. The electric field distribution of the designed electrode model was simulated by MAXWELL 3D® simulation software, and the discharge parameters were measured. Through a series of experiments, we investigated the impact of optimal designs, such as the dielectric of the electrode, immersion depths, and curvature radii of the electrode on the generation characteristics of plasmas. In addition, we designed an equipotential multi-electrode configuration to treat a Methyl Violet solution and observe the discoloration effect. The experimental and simulation results indicate that the designed electrodes can realize glow discharge with a relative low voltage, and the generated plasmas covered a large area and were in stable state. The efficiency of water treatment is improved and optimized with the designed electrodes.

Keywords: water surface, plasma, electrode model, dielectric barrier discharge, electric field

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

1 Introduction

Recently, plasma water treatment technology has been investigated for several environmental applications, including treatment of wastewater and drinking water [1]. Plasma water treatment technology is a new approach that has been used in combination with UV-induced photochemical reactions, sonochemical reactions, and VUV irradiation [2–6]. Compared with traditional water treatment technologies, the plasma treatment technology presents the advantages of fast purification and no secondary pollution [7,8]. The existing plasma water treatment technology has primarily used the methods of injecting bubbles into the wastewater or spraying the wastewater into the air [9–13]. However, there exist some problems to be solved, such as low efficiency and power loss. To improve some deficiencies in plasma water treatment technology, a new electrode is designed and employed in this study. Because of the air gap formed by the electrode with the water surface, a glow discharge occurs, and a large, stable plasma area is acquired for treating wastewater at lower voltages. The electric field distribution of the designed electrode model is simulated by MAXWELL 3D® simulation software. The discharge parameters generated in the glow discharge process are measured, and discharge phenomena are observed. By optimizing the structures, plasmas with stable state and large area are achieved. This study not only improves the existing problems to a certain extent, but also provides theoretical bases and experimental proof for practical application in the plasma water treatment field.

2 Experimental setup

2.1 Main discharge circuit

In this study, a sine-wave power with a frequency of 20 kHz and a 0±10 kV voltage output by sinusoidal pulse width modulation (SPWM) was adopted. The schematic diagram of the main discharge circuit is shown in Fig. 1. 220 V AC voltage was rectified to a low DC voltage, and the ripple wave of the low DC voltage was reduced by a filter resistance. An inverter circuit was composed of a MOSFET converter, and the driving signal of the MOSFET was obtained by a SPWM generator UC3825. The high-frequency low voltage was boosted by a high-frequency step-up transformer, and the ratio of the transformation was 1:80, generating the high-frequency, high-voltage waveform.
2.2 Discharge electrodes

The structure diagram of the designed electrode is shown in Fig. 2. An electrode covered with a PTFE dielectric, which was called the water surface electrode, was placed on the water surface. The other electrode, with or without the dielectric barrier PTFE, was placed in the water and named the water electrode. Because PTFE is a hydrophobic material, the contact angles will be changed by different solutions. Therefore, the main focus of this study was the contact angle with the water. According to the Young formula \[ \gamma_d - \gamma_{sv} + \gamma_l \cos \theta = 0, \] the contact angle was calculated to be 115°.

![Fig.2 The structure diagram of the electrode laboratory model](image)

3 Results and discussion

In this study, a new electrode was designed and employed. Through a series of contrasting experiments, we discuss the impact of optimal designs on the discharge characteristics for the designed electrode models.

3.1 Dielectric of the water electrode

To investigate the impact of the dielectric of the water electrode, water electrodes covered with and without the dielectric were used. The maximum electric field strength of the designed electrode model was simulated by MAXWELL 3D® simulation software. During the experiment, a voltage of 4 kV was applied to the water surface electrode and the water electrode was kept grounded. Table 1 lists the discharge parameters with and without the dielectric, and the electric field simulation results are shown in Fig. 3.

<table>
<thead>
<tr>
<th>Maximum electric field strength (V/m)</th>
<th>Initial discharge voltage (kV)</th>
<th>Stable discharge voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without dielectric</td>
<td>2.08 \times 10^7</td>
<td>2</td>
</tr>
<tr>
<td>With dielectric</td>
<td>1.72 \times 10^7</td>
<td>4</td>
</tr>
</tbody>
</table>

![Fig.3 Electric field simulation results with and without dielectric](image)

(a) Without dielectric, (b) With dielectric

It can be concluded from Fig. 3 that the electric field strength in the small air gap formed by the water surface electrode and the water surface was much greater than that in the other areas. If the air gap increased, an electron avalanche developed dramatically, leading to a filamentary discharge. The employed electrode was designed with a small air gap to inhibit the development of electron avalanche and restrain filamentary discharge, which were beneficial for achieving glow discharge. Therefore, the air gap played a crucial role in the generation characteristics of the water surface dielectric barrier discharge plasmas.

From Fig. 3, we can see that the electric field strength in the air gap without the dielectric was larger than that with the dielectric. Combined with the parameters given in Table 1, the initial discharge voltage for the water electrode without the PTFE dielectric was
lower than that with the PTFE dielectric. When two electrode models were applied with the same voltage, the discharge phenomena for the water electrode without the PTFE dielectric were more violent than that with the PTFE dielectric. In addition, a stable glow discharge at atmospheric pressure was obtained by the water electrode without the PTFE dielectric, as shown in Fig. 4(a). However, filamentary discharge occurred frequently for the water electrode with the PTFE dielectric. It was easy for the discharge to be transformed into a breakdown discharge when a higher voltage was applied to the surface water electrode. In addition, the discharge voltage could be effectively reduced by using the water electrode without the dielectric. And thus the water electrode without the dielectric will be adopted, and atmospheric pressure glow discharge can then be realized, and a stable homogeneous plasma area will be generated.

3.2 Immersion depths of the water surface electrode

To investigate the impact of immersion depth on the plasma parameters, the water surface electrode was placed at the immersion depths of 0, 1/4, 1/2, and 3/4 of the whole electrode. Table 2 lists the discharge parameters for different immersion depths, and the electric field simulation results are shown in Fig. 5.

From Table 2 and Fig. 5, it is clear that as immersion depth increased, the maximum electric field strength decreased. Therefore, a higher voltage was applied to the electrodes to increase the electric field strength in the air gap, requiring primary electrons to have more energy to break down the air gaps and initiate the discharge. The field strength reached a maximum for the immersion depth of 0, i.e., the electrode was tangent to the water surface, as shown in Fig. 5(a). Therefore, combined with the actual process of plasma treatment, the working efficiency and performances could be effectively improved by placing the electrode tangent to the water surface.

3.3 Curvature radius of the water surface electrode

In this experiment, water surface electrodes with curvature radii of 2 mm, 4 mm, and 6 mm were designed. The water electrode without the PTFE dielectric was employed, and the thickness of the insulation was kept constant. The strong electric-field area was obtained by Photoshop software. Table 3 lists the discharge parameters for different curvature radii, and the electric field simulation results are shown in Fig. 6.

<table>
<thead>
<tr>
<th>Immersion depth</th>
<th>Maximum electric field strength (V/m)</th>
<th>Initial discharge voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.08 × 10^7</td>
<td>2</td>
</tr>
<tr>
<td>1/4</td>
<td>1.69 × 10^7</td>
<td>2.1</td>
</tr>
<tr>
<td>1/2</td>
<td>1.48 × 10^7</td>
<td>2.2</td>
</tr>
<tr>
<td>3/4</td>
<td>1.43 × 10^7</td>
<td>2.2</td>
</tr>
</tbody>
</table>

(a) Without dielectric, (b) With dielectric
Fig.4 Discharge waveform and phenomena in stable discharge

Fig.5 Electric field simulation for different immersion depths
Table 3. Discharge parameters for different curvature radii

<table>
<thead>
<tr>
<th>Curvature radius (mm)</th>
<th>Water surface electrode</th>
<th>Maximum electric field strength (V/m)</th>
<th>Strong electric-field area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.85 \times 10^7</td>
<td>2.7148</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.52 \times 10^7</td>
<td>4.3361</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1.29 \times 10^7</td>
<td>4.2418</td>
<td></td>
</tr>
</tbody>
</table>

As seen in Fig. 6, with increasing curvature radius, the field strength decreased and the air gap was elongated to generate a larger plasma area. In addition, it can be concluded from Table 3 that the field strength kept decreasing as the strong field area remained constant. This trend for the discharge area was in accordance with the simulation results, as shown in Fig. 7. Therefore, the largest plasma area could be obtained with the curvature radius of 4 mm.

4 Equipotential multi-electrode model on the water surface

To further obtain a stable and homogeneous plasma area, an equipotential multi-electrode was designed as the water surface electrode, as shown in Fig. 8. We discuss the influences of major factors, such as the horizontal distance \( L \) between adjacent electrodes on the water surface and the vertical dimension \( H \) between the water surface electrode and the water electrode, on the generation characteristics of plasmas. The multi-electrode configuration was adopted to treat a Methyl Violet solution and observe the decolorizing effects.

4.1 Electric field distribution

4.1.1 Horizontal distance

In this study, two electrodes with different horizontal distances of 0 mm and 5 mm were employed. The vertical dimension stayed the same, 10 mm. Table 4 lists the discharge parameters for the equipotential multi-electrode configuration with different horizontal distances, and the electric field simulation results are shown in Fig. 9.

Table 4. Discharge parameters with different horizontal distances

<table>
<thead>
<tr>
<th>Horizontal distance (mm)</th>
<th>Maximum electric field strength (V/m)</th>
<th>Initial discharge voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.84 \times 10^7</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>1.80 \times 10^7</td>
<td>2</td>
</tr>
</tbody>
</table>

From Fig. 9 and Table 4, we can see that the electric field distribution and the initial discharge voltage
were consistent with each other for these two air gaps. Therefore, the impact of horizontal distance on the experimental results could be neglected.

Therefore, an appropriate vertical distance can only realize a greater electric field strength but also achieve a much larger wastewater treatment capacity.

4.2 Decolorization experiment with Methyl Violet solution

In this experiment, the optimized multi-electrode configuration was used to decolorize a Methyl Violet solution. The structure diagram of the electrode configuration is shown in Fig. 11. A voltage of 4 kV was applied to the water surface electrode, and the water electrode remained grounded during the experiment. Samples were withdrawn at 1 min, 3 min, 5 min, and 10 min and analyzed by UV spectrophotometry at a maximum absorption wavelength of 581 nm. According to the formula $\frac{A_0 - A_t}{A_0} \times 100\%$ ($A_0$: the maximum absorption wavelength in the initial solution; $A_t$: the maximum absorption wavelength in the treatment solution). The decoloration rate was calculated accordingly. The discharge waveforms and phenomenon are shown in Fig. 12. The UV spectrum of the Methyl Violet solution is shown in Fig. 13, and the decoloration rate of the Methyl Violet solution is shown in Fig. 14.
From Fig. 12, it is clear that a stable homogeneous plasma area was obtained by using the equipotential multi-electrode configuration on the water surface. As the organic molecules diffused during the treatment \[19\], the solution color became lighter. From Fig. 13 and Fig. 14, we find that the peak absorbance of the Methyl Violet solution gradually decreased, and the decoloration increased with time. When the Methyl Violet solution was treated for 10 min, the decoloration rate was over 90%.

5 Conclusion

In this study, a new electrode on the surface of water was designed. Using MAXWELL 3D® electric field simulation software, the field distribution and effect of the air gap were investigated. Through a series of contrast experiments, the impact of the insulating medium, immersion depth, and curvature radius of the water surface electrode on the discharge characteristics was thoroughly discussed for the designed electrode laboratory model. Moreover, the impact of the relative electrode position on the discharge characteristics was investigated for the equipotential multi-electrode configuration. The conclusions are summarized as follows.

a. The electric field strength in the air gap formed by the water surface electrode and the water surface had significant effects on the plasma generation characteristics. The field strength of the air gap can be affected by such factors as the insulating medium, immersion depth, and curvature radius of the water surface electrode. A suitable electrode layout can effectively reduce discharge voltage and result in a steady, uniform, large plasma area.

b. An equipotential multi-electrode configuration was designed for the water surface electrode. The electric field strength in the air gap can be changed by the horizontal and vertical distances. Selecting an appropriate electrode structure can not only effectively increase the electric field strength in the air gap, but also improve the efficiency of wastewater treatment.

c. The electrode laboratory models could effectively improve some problems in the existing plasma water treatment technology. A stable and large plasma area was obtained with low applied voltage. Compared to the traditional electrode, the designed electrode model simplified the installation of aeration and atomization devices, and thus presented a simple structure.

References


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