Simulated and experimental studies on the array dielectric barrier discharge of water electrodes

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Abstract
A kind of dielectric barrier discharge (DBD) device composed of water electrodes with 3 × 3 forms can produce large-area low-temperature plasmas at atmospheric pressure. To reflect the discharge characteristics of DBD better, a dynamic simulation model, which is based on the voltage controlled current source (CCS), is established, then the established model in Matlab/Simulink is used to simulate the DBD in air. The voltage–current waves and Lissajous at a voltage of 10 kV, 11 kV and 12 kV peak value with a frequency of 15 kHz are studied. The change of the discharge power of DBD with a different amplitude and frequency of applied voltage is also analyzed. The result shows the voltage–current waves, Lissajous and discharge power of DBD under different conditions from the simulation agree well with those of the experiment. In addition, we propose a method to calculate the dielectric barrier capacitance \( C_d \) and the gap capacitance \( C_g \), which is valid through analyzing the variation of capacitance at different voltage amplitudes.

Keywords: dielectric barrier discharge, Matlab/Simulink, lissajous, dielectric barrier capacitance, gap capacitance

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

1. Introduction

Recently, the non-equilibrium plasma has numerous applications on surface treatment [1], layer deposition [2], ozone generation [3], biological applications [4] and so on, which shows the superior economic and environmental benefits. At atmospheric pressure, DBD is an important way to generate non-equilibrium plasmas that have the advantages of large-area and moderate energy density, therefore, DBD has received wide attention from domestic and international researchers.

Compared with corona discharge, arc discharge and other discharges, DBD can use its structure to avoid forming a spark or arc discharge [5] and generate homogeneous plasmas. At present, researchers study discharge characteristics under different conditions by setting up a corresponding experimental apparatus or establishing an appropriate model. However the discharge characteristics of DBD are affected by some factors, such as the structure of the reactor, characteristics of power source, gas source, experimental environment and personal factors, which makes the process of experiment trivial and time-consuming. The researchers are more likely to study the characteristics of DBD by using code or establishing model in software [6–8]. There are numerical model and electrical model developed in DBD research. The numerical model is established based on the continuity equations, but it involves various gas ionization processes and boundary conditions, which are not only complicated to set up but also requires a great amount of calculation. In the electrical model, the discharge progress is regarded as the equivalent electrical
circuit, which complies with a power law. It can reveal the relations between the internal electrical parameters (discharge current, discharge voltage, consuming power, gas voltage, etc) and applied power well. Moreover the time consumed by this model’s computation is usually less one minute. Thus more researchers use the electrical model to study the interaction between the power supply and the DBD device.

The electrodes of DBD are usually made of metal materials like tungsten, copper, or zinc because of their high melting points. But metal electrode is easily eroded by the active substances that DBD generates during a long-time discharge. Some domestic researchers have conducted a few DBD experiments with liquid electrodes. Shao and Yu studied the progress of gas discharge produced with repetitive nanosecond pulses and water-electrode DBD equipment [9]. Dong and Liu studied the mechanism of spiral pattern and spiral defect chaos of discharge phenomenon caused by DBD instruments composed by two conductive solution electrodes and resolved the relationship with the voltage and electric current in the circuit [10]. However, by contrast the research of the experiment and simulated model on array DBD of water electrodes is rarely reported.

In this paper, we invent an array DBD instrument with nine water electrodes. The electrodes are formed by $3 \times 3$ array on plane. A DBD equivalent electrical model is deduced theoretically based on the voltage controlled current source. Then the equivalent capacitances of the discharge gaps $C_g$ and the dielectric barrier $C_d$ are calculated in the array DBD of water electrodes. A dynamic simulated model is established in Matlab/Simulink [11]. We can obtain some parameters (the Lissajous, discharge current and discharge power), and have some analysis and discussion binding the experiment.

2. Experimental setup

Experiments are conducted in an environment of 20°C temperature and 40% humidity. Figure 1 is the picture of the experimental setup, which shows that the DBD reactor is the array type consisting of nine bottles with inner radius $R_i$ and outer radius $R_o$. Each bottle is filled with $L$ height of tap water. The conductivity of tap water in glass is $240 \, \mu$S cm$^{-1}$, which is lower than other kind of metal. The total resistor of tap water is calculated in equations (11), (12). There is a wire immersed in each of the containers and connected to an AC power supply. Frequency and amplitude of voltage can be adjusted in the range of 5–20 kHz and 0–30 kV. The middle and the four corners of water electrodes connect to AC high voltage, others connect to ground. During discharge the tap water and the bottles act as a liquid electrode and solid dielectric respectively. The images of discharge are taken by a Nikon D7200 digital camera with an exposure time of 1/30 s.

Figure 2 is schematic of the experimental system. The voltage applied to the electrodes is measured via a 1000:1 high-voltage probe (Tektronix: P6015A, 75 MHz, 20 kV, 1000×). A 47-nF measuring capacitor is in series in the DBD circuit, it is easy to obtain discharge current and transported charges through the measuring capacitor. The current probe (Tektronix: TCP0030, 120 MHz) is used for displaying the waveform of the discharge current on the oscilloscope (Tektronix, DPO2014B, 1 GS s$^{-1}$, 100 MHz). Also, a low-voltage probe (Tektronix, P2220) is placed on both ends of measuring capacitor. The applied voltage and the voltage of the measuring capacitor are transported to CH1 and CH2 of the oscilloscope respectively. Thus an enclosed quadrilateral shape, called Lissajous, is gained on the oscilloscope during the period.

3. Analysis of the equivalent circuit

The discharge of DBD in air gap consists of a large amount of micro-discharge discretely in time and space, therefore the simulation of DBD is usually based on the simulation and the equivalent of micro-discharge. The equivalent capacitances of our device are calculated taking into account the topology of a coaxial capacitor with two different dielectric materials glass and air, the way of calculating the equivalent capacitances will be represented in section 5. The equivalent circuit of micro-discharge is different when the discharge turns on and turns off. When the applied voltage does not exceed the
electric breakdown in the gap between electrodes, the discharge turns off. The equivalent electric model is considered as two capacitors in serial in the circuit, among \( C_g \) and \( C_d \) representing the equivalent gas gap and the equivalent dielectric barriers respectively, as shown in figure 3(a). When the applied voltage is higher than the breakdown voltage, the discharge begins. The equivalent electric model contains a nonlinear gaseous discharge due to the alteration of gas relative permittivity [12]. Some researchers simulate the micro-discharge progress through using variable resistance, zener diode, or resistor by silicon-controlled switch respectively [13, 14]. But the discharge of DBD is a transient progress, there will be a certain error if adopting the above methods. The CCS model does well [15]. The CCS is a current source controlled by a voltage source according to a law of variation which translates the non-linearity. The equivalent electric circuit of the discharge is shown in figure 3(b).

In the equivalent electric circuit, \( V(t) \) represents the applied voltage, \( i(t) \), \( i_d(t) \) and \( i_g(t) \) are the total current, the displacement current in the dielectric barriers and the displacement current in the gas gap respectively. \( i_{ccs}(t) \) represents the discharge current controlled by the voltage controlled current source, \( C_g(t) \) is variable capacitance, \( R_f \) represents resistance of the micro-discharge, \( V_g(t) \) and \( V_d(t) \) represent the voltage across the gas gap and the dielectric barriers respectively, \( U(t) \) is a voltage resource.

By using Kirchhoff’s voltage and current law:

\[
i(t) = i_d(t) = C_d \frac{dV_d(t)}{dt}.
\]

(1)

The displacement current of the gas gap:

\[
i_g(t) = C_g \frac{dV_g(t)}{dt} = i(t) - i_{ccs}(t).
\]

(2)

The supply voltage:

\[
V(t) = V_g(t) + V_d(t).
\]

(3)

For the time derivative:

\[
\frac{dV(t)}{dt} = \frac{dV_g(t)}{dt} + \frac{dV_d(t)}{dt} = \frac{1}{C_g} [i(t) - i_{ccs}(t)] + \frac{i(t)}{C_d}.
\]

(4)

Substitute equations (1)–(3) into (4):

\[
i_{ccs}(t) = \left(1 + \frac{C_g}{C_d}\right) i(t) - C_g \frac{dV(t)}{dt}.
\]

(5)

As shown in equation (5), the discharge current value changes with the change of the applied voltage, the gas gap current changes with the applied voltage slope, \( i_{ccs}(t) \) at any moment always corresponding to \( i(t) \) uniquely. Thus only the model using CCS can reflect the nonlinear change of discharge of DBD truly.

4. Electric simulation model

A model is set up in Matlab/Simulink based on the equivalent electric circuit, as seen in figure 4.

In the model, the discharges are controlled by two switches of SW1 and SW2, and the status of SW1 and SW2 is determined by the output level that the Pulse1 and Pulse2 control by OR operation. The Pulse1 \((-t_1 - t_2)\) and Pulse2 \((-t_3 - t_4)\) are calculated according to equations (14)–(17). \( t_1 \) and \( t_2 \) are starting and ending moment of micro-discharge during positive periodic respectively; \( t_3 \) and \( t_4 \) are starting and ending moment of micro-discharge during negative periodic respectively. Pulse1 is high only from \( t_1 \) to \( t_2 \) and Pulse2 is high only from \( t_3 \) to \( t_4 \). When the voltage reaches the breakdown threshold, discharge turns on \((-t_1 - t_2, t_3 - t_4)\), an output high level that is obtained by OR operation makes SW1 off and SW2 on; in contrast when discharge turns off, an output low level that is obtained by OR operation makes SW1 on and SW2 off. In the circuit of model, the \( C_g \) of discharge-off decreases to \( C_{g1} \) of discharge-on and \( C_g = C_{g1} + C_{g2} \).

Through a large simulation debugging, the simulation is
better when $C_{g1} = 0.7C_g$. In the model, the parasitic capacitance between the high potential and ground during the discharge and impedance of the wire and connectors in the circuit needs to be considered. A capacitance $C = 0.1 \text{ pF}$ and a parallel RL component are added to represent the effect of parasitic capacitance and impedance of the wire respectively. Among the RL components, $R = 4 \text{ k} \Omega$, $L = 0.5 \text{ mH}$ are appropriate when comparing with the experiment.

### 5. Calculation of simulation parameters

For simple DBD device, like parallel plate, the calculation of dielectric barrier capacitance $C_d$ and gas gap capacitance $C_g$ are as follows:

$$C_d = \frac{\varepsilon_0 \varepsilon_d S_d}{2l_d}$$  \hspace{1cm} (6)

$$C_g = \frac{\varepsilon_0 \varepsilon_g S_g}{l_g}$$  \hspace{1cm} (7)

But for the bottles, the discharge space is irregular, the value of $l_d$ and $l_g$ is not constant. Thus equations (6), (7) cannot be used to calculate $C_d$ and $C_g$ in this device. In figure 5(a), the capacitance between two parallel cylindrical electric conductors is calculated using equation (8) with their $L$ length, $R$ radius, the distance between them being $2x_0$, the following capacitance is obtained [16]

$$C = \frac{4\pi \varepsilon_0 \varepsilon_g}{\ln \left[9 + \left(\frac{R}{x_0}\right)^2\right]} L$$  \hspace{1cm} (8)

For two bottles, $C_{g0}$ and $C_{d0}$ are calculated using the following equations (9), (10)

$$C_{g0} = \frac{4\pi \varepsilon_0 \varepsilon_g}{\ln \left[9 + \left(\frac{R_0}{x_0}\right)^2\right]/[1 + (R_0/x_0)^2]} L$$  \hspace{1cm} (9)

$$C_{d0} = \frac{4\pi \varepsilon_0 \varepsilon_d}{2\ln \left[9 + \left(\frac{R_0}{x_0}\right)^2\right]/[1 + (R_0/x_0)^2]} L$$  \hspace{1cm} (10)

Among them $R_0 = 16 \text{ mm}$, $R_1 = 14.3 \text{ mm}$, $\varepsilon_0 = 8.854 \times 10^{-12} \text{ F m}^{-1}$, $\varepsilon_s = 1$, $\varepsilon_d = 3.2$, $L = 40 \text{ mm}$, $d = 1 \text{ mm}$. In the array bottles, $C_{g0}$ and $C_{d0}$ of two bottles with the different positions are calculated, then the total $C_g$ and $C_d$ are obtained. There are five different distances of the water electrodes: 16.5 mm, 23.3 mm, 33.0 mm, 36.9 mm and 46.7 mm. Each distance contains a variety of combinations $n$. For example, $n = 6$ represents 1–3, 1–7, 7–9, 3–9, 2–8, 4–6 (each bottle

![Figure 4. Dynamic electrical simulation model of DBD in Matlab/Simulink.](image)

![Figure 5. The simplified graphic of the array DBD.](image)

**Table 1.** The calculation of $C_g$ and $C_d$.

<table>
<thead>
<tr>
<th>$x_0$ (mm)</th>
<th>$C_{g0}$ (pF)</th>
<th>$C_{d0}$ (pF)</th>
<th>$n$</th>
<th>$C_g$ (pF)</th>
<th>$C_d$ (pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.5</td>
<td>2.7</td>
<td>4.2</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23.3</td>
<td>2.4</td>
<td>3.7</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>33.0</td>
<td>2.2</td>
<td>3.5</td>
<td>6</td>
<td>86.6</td>
<td>135.0</td>
</tr>
<tr>
<td>36.9</td>
<td>2.2</td>
<td>3.4</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>46.7</td>
<td>2.1</td>
<td>3.4</td>
<td>2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
has number seen in figure 5(b). The results of the calculation are shown in table 1.

The total resistor of the tap water is calculated as follows:

\[ R_w = \frac{D}{\delta S} \]  \hspace{1cm} (11)

\[ R = \frac{2R_w}{N} \]  \hspace{1cm} (12)

In the above two equations, \( R_w \) is the resistor of tap water of a bottle, \( R \) is the total resistor of tap water in the DBD reactor. \( \delta \) is the conductivity of tap water with the value of 240 \( \mu \text{s cm}^{-1} \). \( S \) is the area of discharge of two adjacent bottles, its value is 11.44 cm\(^2\). \( N \) is the number of the discharge region and \( N = 12 \). \( D \) is the length of water electrode at the discharge direction, its value is in the range of 0–2\( R \). The max value of \( R \) is 173.6 \( \Omega \), which is small relative to the resistor of the whole circuit.

Based on the mechanism of gas discharge, the initial discharge voltage is estimated as follows [17]:

\[ U_b = 3000 \times l_g + 2 \times l_d \times \frac{3000}{\varepsilon_d}. \]  \hspace{1cm} (13)

In the experiment condition, \( l_g = 1 \text{ mm}, \) \( l_d = 1.7 \text{ mm}, \) \( U_b = 6.4 \text{ kV} \) is obtained. Duty ratio of the pulse is calculated by equations (14)–(18)

\[ t_1 = \frac{1}{2\pi f} \arcsin \left( \frac{U_b}{U_p} \right) \]  \hspace{1cm} (14)

\[ t_2 = \frac{1}{4f} \]  \hspace{1cm} (15)

\[ t_3 = \frac{1}{2\pi f} \arcsin \left( \frac{U_b}{U_p} \right) \]  \hspace{1cm} (16)

\[ t_4 = \frac{3}{4f} \]  \hspace{1cm} (17)

\[ D = \frac{t_2 - t_1}{T} = \frac{t_4 - t_3}{T}. \]  \hspace{1cm} (18)

According to the theory of gas discharge, discharge power of DBD can be calculated by equation (19) [18]

\[ P = 4fC_d \frac{C_d}{C_d + C_g} U_m (U_b - U_m). \]  \hspace{1cm} (19)

In this formula, \( U_m \) is the maintaining discharge voltage, being approximately equal to \( U_b \).

6. Results and discussions

The discharge picture of the array bottles is shown in figure 6. In this figure, the discharge appears in the gap between the two bottles, which is emitting purple light. The bottles have two functions as a dielectric capacitor: (i) it can limit the movement of charged particles and makes the micro-discharge short pulses; (ii) it not only prevents spark discharge but also makes uniform discharge emerge easily in the gap. Filaments density of discharge increases with the increase of applied voltage amplitude. New micro-discharge occurs in the place without wall charges, and the wall charges produced by adjacent discharge filaments overlap together. Interaction between micro-discharge are more obvious with the increase of density of micro-discharge. The discharge graduates from a local point to a large area of purple hybrid form, then fills the whole space.

The value of \( C_d \) and \( C_g \) is 128 pF and 104 pF respectively from experiment Lissajous at the value of peak voltage is 10 kV and the frequency is 15 kHz, which is compared with the \( C_d \) is 135.0 pF and \( C_g \) is 86.6 pF from the calculation. Because \( C_d \) is quantitatively related to thickness \( l_d \), permittivity \( \varepsilon_d \) and effective area of the dielectric barrier, therefore there is a little error of \( C_d \) between experiment and calculation. However, the ionization of the gas level is different under a different voltage, the value of \( C_g \) obtained from experiment is 17.6 pF larger than theoretical calculation. In figure 7, the value of \( C_d \) rises slightly and the value of \( C_g \) declines observably from 9 kV to 12 kV, which is the same result in [19, 20]. The discharge enhances with the increase of voltage, and the charged electron numbers increase, which makes \( \varepsilon_g \) lower. Hence the theoretical
calculation on $C_g$ approach experiment when the applied voltage is higher.

In figure 8, Lissajous of DBD discharge is a closed parallelogram, its left and right sides correspond to discharge phase, and its up and down sides correspond to extinction of the discharge. We can see that the enveloped area of Lissajous increases with the increase of the applied voltage, which suggests the increase in discharge power with the applied voltage amplitude. The comparison between simulated and experimental figure shows that the simulation diagram is slightly offset to the experiment, but the area error is within 1%.

The experimental and simulated results of the voltage and current waveforms for different applied voltage

Figure 8. Experimental and simulated Lissajous figures under different applied voltage amplitudes (a), (b) and (c) Lissajous figures at 10 kV, 11 kV and 12 kV).

Figure 9. Experimental and simulated applied voltage and total current waveforms under different applied voltage amplitudes (a), (c) and (e) experimental applied voltage and total current waveforms at 10 kV, 11 kV and 12 kV; (b), (d) and (f) simulated applied voltage and total current waveforms at 10 kV, 11 kV and 12 kV.)
amplitudes are shown in figure 9. In figure 9(a), the discharge occurs when the applied voltage is higher than the breakdown value and the initial electrons move to anode under the action of electric field at the start time of the positive periodic, and deposit on the surface of the bottle. In the tens of nanoseconds, a large amount of electrons on the bottle’s surface produce an inverse electric field along the surface, which makes the gas gap voltage decrease. The discharge turns off when the applied voltage increases to the max value 10 kV. After a quarter of period, the applied voltage reverses. The discharge is stronger because the applied electric field overlays with the electric field produced by the surface electrodes. It is seen obviously that the max amplitude of current in the negative periodic is bigger than that in the positive periodic. Then it is the extinction period after the applied voltage that reaches the max value. The discharge is a transient process in essence, including discharging, going-out, discharging again, going-out again. It is clear that the amplitude of current pulse rises from 0.2 A to 0.3 A with the increase of the applied voltage from 10 kV to 12 kV, which suggest increase of intensity of the discharge with the applied voltage. The variation trend of simulation is roughly in agreement with the experiment.

From figure 10, for the array DBD of water electrode, the discharge power has a roughly linear relation to frequency, which is seen in equation (19). At the same frequency, the higher the applied voltage, the bigger the discharge power. When the structure parameters of the DBD reactor are fixed, improving the discharge power can add the discharge filament effectively, and increase the number of high-energy electrons. When voltage frequency is 16 kHz, applied voltage increased from 9 kV to 12 kV, discharge power increased from 76 W to 142 W. The power increases 22 W every increasing 1 kV. With increasing of frequency of applied voltage from 15 kHz to 18 kHz, the consuming power increases from 115 W to 134 W. When the peak amplitude of the voltage is 9 kV, the consuming power gains more at a frequency of 19 kHz because the frequency is closer to the resonance frequency of our device. The consuming power at $f = 19$ kHz and $V_p = 9$ kV is almost equal to that at $f = 18$ kHz and $V_p = 10$ kV. Sometimes in order to maintain a constant power level in the reactor, the applied voltage amplitude diminishes by increasing the frequency. Figure 10 shows that the consuming power of simulation is near the corresponding experimental value, which indicates the model based on CCS can simulate the micro-discharge of array DBD well.

7. Conclusion

For the array DBD of water electrodes, we propose a way to calculate the equivalent $C_f$ and $C_d$. The value of $C_f$ is in good agreement with the experimental measurements. However, there is a big error of $C_d$ between simulation and experiment when applied voltage is $V_p = 10$ kV and $f = 15$ kHz. The level of ionization degree strengthen with the increase of voltage amplitude, which makes the error in the ideal range. The calculation way for $C_f$ and $C_d$ is feasible.

In addition, the model is established based on CCS to simulate the dynamic discharge process of array DBD. In the model, Lissajous curves, discharge current and consuming power agree well with experiment. The relation between consuming power, applied voltage and frequency is consistent with the theoretical analysis. The research about the array DBD factors such as the gas gap distance and dielectric substance having influence on discharge can be done to optimize array DBD plasmas reactor design and improve the efficiency of discharge.

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