Characteristics of Capacity Coupled Discharge in Atmospheric Pressure Air

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Keywords : capacity-coupled multi-discharge, dielectric barrier discharge, power, streamer

Research on atmospheric pressure nonthermal plasmas is motivated by various industrial applications. Capacity-coupled multi-discharge (CCMD) has been proposed as a large-scale, atmospheric pressure, dense plasma source. The discharge gaps in the CCMD consist of a common electrode and a number of compact electrodes which are directly coupled with small capacitors for quenching the discharge. This paper describes characteristics of capacity coupled discharge in atmospheric pressure air with focusing influence of input power into the discharge on gap length of point-to-plane electrode configuration.

Figure 1 shows the Vxexperimental setup. The needle electrode was connected to the quenching capacitor. A damping resistor $R_0$ was employed to reduce the inductance and capacitance (LC) resonant oscillation due to low impedance of the discharge plasma after breakdown. A typical value of the resistance $R_0$ was 50 kΩ. The gap length was changed from 1 to 5 mm. The discharge gap was placed in ambient air. We used mainly the $V$-$Q$ Lissajous diagram to measure the deposited energy. The electric charge was measured using a 0.05 µF capacitor $C_L$.

Figure 2 shows the input power to the plasma as a function of the applied voltage for two different gap lengths at 9.4 pF of quenching capacitor capacitance. Here, the input power to the plasma $P$ can be expressed by the following equation;

$$P = 2k f W_p = 2k f \left( \frac{R_0}{R_p + R_0} \right) \left( \frac{1}{2} \right) C_q V_{BD}^2$$

(1)

where $k$ is a number of discharges per half period of the applied voltage, $R_0$ is the resistance of the circuit, $R_p$ is the plasma resistance, $C_q$ is the capacitance of the quenching capacitor, $V_{BD}$ is the breakdown voltage. It is clearly seen from Fig. 2 that the input power at 1 mm gap length increases discretely as the applied voltage increases of every 2 kV$_{pp}$. These facts coincide with the prediction from Eq. (1). The input power at 5 mm gap length increases linearly with increasing applied voltage. From the discharge current waveform measurement, an amount of the movement electric charge for one microdischarge at 5 mm gap length is much smaller than that at 1 mm gap length. The value of the amount charge of CCMD at 5 mm gap length is similar to that of conventional dielectric barrier discharge (DBD).

Figure 3 shows the input power into the discharge as a function of the gap length for two different discharge conditions; CCMD and DBD. The applied voltage was set to CCMD ignition voltage for each gap length ($k=1$). The capacitance of the quenching capacitor for CCMD is 9.4 pF. The 2 mm-thickness soda glass (7.5 in relative permittivity) plane for DBD is employed as dielectric barrier and the glass plane is set on the high voltage plane electrode. Figure 3 shows that the input power of DBD increases linearly with gap length. In the other, a discontinuous change is confirmed between the gap lengths of 2.0 and 2.5 mm of CCMD. This discontinuity means the transition of the discharge from the spark-like to the corona-like. The input power of CCMD is almost 5-10 times larger than that of DBD at shorter gap length than 2.5 mm, whereas the input power of CCMD almost agrees with that of the DBD at larger gap length than 2.5 mm.
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This paper describes characteristics of capacity coupled discharge in atmospheric pressure air with focusing influence of gap length of point-to-plane electrode configuration on input power into the discharge. The discharge can be quenched in short time duration by inserting a small capacitance capacitor between the electrode and the ground. We employed a needle electrode and a coaxial cable as the quenching capacitor. The discharge was successfully quenched within 25 ns in duration according to 9.4 pF in a capacitance of the quenching capacitor. The discharge was classified as two modes; a spark mode and a corona mode. At the spark mode, the power consumed in the discharge plasma was almost 10 times as large as that of a conventional dielectric barrier discharge. At the corona mode, the consumed energy was almost same value with that of the dielectric barrier discharge. A velocity of the discharge development was obtained to be $3 \times 10^5 \text{ m/s}$ by an optical measurement.

Keywords: capacity-coupled multi-discharge, dielectric barrier discharge, power, streamer

1. Introduction

Research on atmospheric pressure nonthermal plasmas is motivated by various industrial applications; ozone generation, surface modification, material cleaning, decomposition of hazardous pollutants, light sources, etc(1-3). A dielectric barrier discharge (DBD) is one of the atmospheric pressure plasma generation methods developed by Siemens as an ozonizer(4). DBD is a typical ac discharge for the production of nonequilibrium thermal plasma at high gas pressure. DBD can occur between two electrodes with narrow gaps of 1 to 5 mm, at least one of which should be covered with dielectric, when an ac voltage is applied to the electrodes. It limits the electric charge transported in the discharge, i.e., limits the current flow to the system and therefore, prevents the thermalization of the plasma.

Capacity-coupled multi-discharge (CCMD) has recently been proposed as a large-scale, atmospheric-pressure, dense plasma source(5). The discharge gaps in the CCMD consist of a common electrode and a number of compact electrodes which are directly coupled with small capacitors for quenching the discharge in a manner similar to the DBD. The CCMD is predicted to have interesting features for industrial applications; it is easy to control the plasma spatially because the discharge consists of only volume discharges without surface discharge; it is easy to control the energy deposited into the discharge plasma by changing the quenching capacitor(6). The self-quenching discharges coupled with small capacitors were employed for other objectives such as UV sources for photoionization of gas lasers(7). However, this is the first case where the self-quenching discharges were used as nonthermal plasma sources.

Experiments have been carried out to understand the behavior of the CCMD. Mase et al. produced multi-discharge using twenty co-axial cables 20 cm in length (20 pF for one cable). The results of these experiments showed that the amount of charge transfer for the 20 multi-discharge was $1.4 \mu C$, which corresponded to $70 \text{ nC}$ charge transfer for a single discharge. The value was 10-100-fold that of the conventional DBD(5). In general, ac voltage power supplies were used to generate the CCMD. Mase et al. also reported that the number of discharges per one ac applied voltage cycle can be controlled by the amplitude of the voltage. The number of discharges per half-period of ac applied voltage was successfully controlled from 1 to 4 by increasing the voltage(8). Takaki et al. reported that the discharge was quenching in short time around 10 ns(9).

In order to use the CCMD for various applications, it is necessary to understand characteristics of the discharge more clearly such as influence of the electrode configuration on amount of the movement electric charge and consumed power. This paper describes characteristics of capacity coupled discharge in atmospheric pressure air with focusing influence of gap length of point-to-plane electrode configuration on input power into the discharge. Furthermore, a velocity of the discharge propagation in the gap was obtained by an optical measurement using a photo-multiplier tube in order to compare with that of a typical streamer discharge.
2. Experimental Procedure

Figure 1 shows the experimental setup of a self-quenching discharge system. The needle-to-plane electrode configuration was employed to fix the plasma position. A brass plane having 8 cm in diameter was used as a high voltage electrode. The needle electrode, which was 1.0 cm in length and 50 µm in tip radius, was connected to the quenching capacitor. A coaxial cable RG58/U (53.5 Ω impedance, 94 pF/m capacitance, 268 nH/m inductance) was used as the capacitor for quenching the discharge. The capacitance of the quenching capacitor can be changed by the cable length at a rate of 94 pF/m. The capacitance used in the experiment was 9.4 pF according to a 10 cm length. A damping resistor \( R_0 \) was employed to reduce the inductance and capacitance (LC) resonant oscillation due to low impedance of the discharge plasma after breakdown. A typical value of the resistance \( R_0 \) was 50 kΩ. The gap length between the needle tip and the plane electrode surface was changed from 1 to 5 mm. The discharge gap was placed in atmospheric air.

The commercial ac voltage was raised to 1:150 by a leakage flux transformer (15 mA, 50 Hz). The raised voltage was 40 kV in maximum peak-to-peak value, and it was applied to the plane electrode. The applied voltage was controlled by a variable transformer (slidac). To make the impedance of the power supply low and to realize the fast rise of the discharge current pulse, a 5.6 µF capacitor \( C_0 \) was connected in parallel with the power supply.

The potential of both electrodes was measured using high-voltage probes (SONY Tektronix P6015A). The discharge current was measured using a current monitor (PEASON CURRENT MONITOR 2877). The current and voltage signals were recorded with a digital storage oscilloscope (SONY Tektronix TDS 3054B). The energy deposited into the discharge system was measured optically using a side-on type Photo Multiplier Tube (Hamamatsu Photonics 1P28).

3. Experiment Results

3.1 Self-quenching Behavior

One of special feature of the CCMD was expected to quench the discharge in short time. At first, we measured time-dependency of the discharge current and the electrode potentials. Figure 2 shows the time-dependency of the potentials of both electrodes at 1 mm gap length and 10.5 kVpp applied voltage. In this case, we employed a 1.0 nF quenching capacitor in order to reduce the decay of the quenching capacitor potential by a charge leakage from the quenching capacitor to the ground through the high-voltage probe. The damping resistor \( R_0 \) was also removed to decreasing influence of voltage drop caused by the circuit impedance and the discharge current. The applied voltage, i.e., the potential of the high-voltage electrode, shows an almost sinusoidal waveform, whereas the CCE potential changes stepwise. The voltage difference between steps is approximately 3 kV, while there is a scattering between 2.5 and 3.5 kV due to the lack of a photo pre-ionization. The voltage difference between steps is considered to be close to the breakdown voltage \( V_{BD} \). If we take 3 kV as the breakdown voltage \( V_{BD} \), the integer \( k \) is calculated as 3 at applied voltages of 10.5 kVpp, respectively, using following equation:

\[
k = \text{Integer Part of } \left( \frac{V_{pp}}{V_{BD}} \right) \quad (1)
\]

where \( V_{pp} \) is the ac potential in peak-to-peak value. These values show good agreement with the number of steps shown in Fig. 2.

Figure 3 shows that the time variation of discharge current and the both electrode potentials \( V_0 \) and \( V_{CCE} \) defined in Fig. 1 at 1 mm gap length and 10.0 kVpp applied voltage. The capacitance of the quenching capacitor \( C_q \) and the resistance of the damping resistor \( R_0 \) are 9.4 pF and 50 kΩ, respectively. The discharge occurred three times for each half cycle of the applied ac voltage as shown in Fig. 2. Figure 3 (a), (b) and (c) show the current and the potentials waveforms at first, second and third discharges, respectively. In all cases, when the discharge begins, the current increases from 0 to 3 A within a short time of about 10 ns. This discharge current value is very large as compared with the current value (typically several tens of mA) of one microdischarge of dielectric barrier discharge\(^{(10)}\). The discharge current charges the quenching capacitor and the CCE potential increases rapidly. The potential of the high-voltage electrode decreases simultaneously due to the impedance of the power source and the damping resistor \( R_0 \). As a result, the electric field strength between the electrodes decreases to almost zero at 10 ns after the discharge ignition, and the discharge is successfully quenched as predicted theoretically. This quenching time is close to that of DBD, e.g., 50
ns as reported by Gibalov and Pietsch (10), 20 ns by Braun et al. (11), and 20 ns from light emitted from discharge plasma reported by Dong et al. (12).

### 3.2 Influence of Gap Length

Figure 4 shows that the time variation of discharge current and the both electrode potentials \( V_0 \) and \( V_{\text{CCE}} \) at 5 mm gap length. Other conditions are same as shown in Fig. 3. In this case of 5 mm gap, the pulsive discharge current is also observed at 5 kV of applied voltage \( V_0 \). The peak value of the discharge current is almost 40 mA which is much less than 3 A shown in Fig. 3. The amount of transfer charge for one discharge is roughly obtained to be 1.5 nC by time-integrating the discharge current waveform. This value almost agrees with the calculating result using the CCE potential difference between before and after the discharge \( \Delta V_{\text{CCE}} \) as \( C_q \times \Delta V_{\text{CCE}} \). The 1.5 nC amount of charge is almost one order less than the value 20 nC at 1 mm gap length obtained using Fig. 3. Moreover, the voltage of the gap, \( V_0 - V_{\text{CCE}} \), after the discharge is still larger than 4.5 kV at 5 mm gap length, whereas the gap voltage after the discharge is almost zero at 1 mm gap length as shown in Fig. 3. This result reveals that the impedance of the discharge is still high and the ionization occurs spatial-partially around the tip of the needle electrode because of highly distorted strong electric field. Generally, that feature of the partial ionizing discharge can be classified as a corona discharge (13)(14). On the other, the impedance of the discharge at 1 mm gap length is extremely small compared with that at 5 mm gap length. The feature of the low impedance pulsive discharge can be classified as a spark discharge; arc-like partially thermalized pulsive plasma (13).

### 3.3 Input Power into the Discharge

Figure 5 shows that the \( V-Q \) Lissajous figure at 1 mm gap length and 10.0 kVpp applied voltage. The capacitance of the quenching capacitor is set to be 9.4 pF. The \( V-Q \) Lissajous figure in Fig. 5 shows a discontinuously stepwise change. This stepwise change implies a large amount of the movement charge by one discharge as same manner with a glow mode DBD (15). The discontinuous change in \( V-Q \) Lissajous figure shows the generation of the discharge, and the number of the discharge per half-cycle of the applied voltage can be obtained to be three from Fig. 5. From the \( V-Q \) Lissajous figure, the difference in electric charge between before and after discharges is almost constant at all discontinuously stepwise changes and is approximately 20 nC, which corresponds to 2.1 kV in the potential difference of the CCE. This value of 20 nC is about 10-100 times as large as the amount of the transfer electric charge (0.1-1 nC) of the typical dielectric barrier discharge in the air at atmospheric pressure (16).

Figure 6 shows that the \( V-Q \) Lissajous figure at 5 mm gap length and 10.0 kVpp applied voltage. The capacitance of the quenching capacitor is set to be 9.4 pF. The \( V-Q \) Lissajous figure as shown in Fig. 5 at 1 mm gap length does not exist, and it is similar to \( V-Q \) Lissajous figure in conventional DBD (16). Figure 6 also shows that the amount of the movement charge by the discharge is almost 15 nC per one half-cycle. The value of 15 nC is ten times larger than the 1.5 nC of the one discharge transferred charge which is obtained with the current waveform shown in Fig. 4. This result indicates that a large number (more than 10) of discharges generates during a half-cycle of applied voltage as same manner with DBD.

Figure 7 shows the input power to the plasma as a function of the applied voltage for two different gap lengths at 9.4 pF quenching capacitor capacitance. The applied voltage is changed from the breakdown voltage to 14 kVpp. The input powers were
determined using $V$-$Q$ Lissajous figure as shown in Figs. 5 and 6. The discharge power at 1 mm gap was calculated using by dividing the $V$-$Q$ Lissajous figure shown in Fig. 5 into small rectangular pieces and summing the areas of all pieces\(^{10}\). Here, the input power to the plasma $P$ can be expressed by the following equation\(^{11}\):

$$P = 2kW_p = 2kf \left( \frac{R_p}{R_p + R_p} \right) \frac{1}{2} C_q V_{BD}^2$$  \hspace{1cm} (2)

where $k$ is a number of discharges per half period of the applied voltage, $R_p$ is the resistance of the circuit, $R_p$ is the plasma resistance, $C_q$ is the capacitance of the quenching capacitor, $V_{BD}$ is the breakdown voltage. Equation (2) implies that the input power increases discretely as the applied voltage increases every 2 kV\(_{pp}\). Moreover, the value of the input power increases about every 5 mW, and increases to an integer number $k$. These facts agree with the prediction from Eq. (2).

The input power at 5 mm gap length increases linearly with increasing applied voltage. The amount of the movement electric charge for one microdischarge at 5 mm gap length is much smaller than that at 1 mm gap length as mentioned in Sec. 3.2. This behavior of the 5 mm gap discharge is similar to that of DBD. The input power of the DBD can be expressed by the following equation:

$$P_{DBD} = 4f C_q e_0^2 \left( e_{in} - \frac{C_p}{C_q} e_0 \right),$$  \hspace{1cm} (3)

where $C = C_p C_d / (C_p + C_d)$, $C_p$ and $C_d$ are the capacitance of the dielectric and the capacitance of the air, respectively. $e_0$ is an applied voltage, $e_{in}$ is a voltage between electrodes when there is no charge on the dielectric surface\(^{10}(16)\). This equation predicts that the input power linearly increases with applied voltage $e_0$. Therefore, the behavior of the input power at 5 mm gap length is similar to that of DBD, is not similar to that predicted by Eq. (2).

4. Discussion

4.1 Comparison with Dielectric Barrier Discharge

Figure 8 shows typical $V$-$Q$ Lissajous figure of dielectric barrier discharge with same electrode configurations as shown in Fig. 1. The gap length and applied voltage are 5 mm and 10.0 kV\(_{pp}\) respectively. The 2 mm-thickness soda glass (7.5 in relative permittivity) plane is employed as dielectric barrier and the glass plane is set on the high voltage plane electrode. The low voltage needle electrode is connected to the capacitor $C_q$ for $V$-$Q$ Lissajous measurement. The shape of the $V$-$Q$ Lissajous figure of DBD shown in Fig. 8 is similar to that of CCMD at 5 mm gap length as shown in Fig. 6.

Figure 9 shows the input power into the discharge as a function of the gap length for two different discharge conditions; CCMD and DBD. The applied voltage was set to CCMD ignition voltage for each gap length ($k$=1). The capacitance of the quenching capacitor for CCMD is set to be 9.4 pF. The experimental condition of DBD is the same as shown in Fig. 8. Figure 9 shows that the input power of DBD increases linearly with gap length. On the other, a discontinuous change is confirmed between the gap lengths of 2.0 and 2.5 mm of CCMD. This discontinuity means the transition of the discharge from the spark-like to the corona-like as mentioned in Sec. 3.2. The input power of CCMD is almost 5-10 times larger than that of DBD at shorter gap length than 2.5 mm, whereas the input power of CCMD almost agrees with that of the DBD at larger gap length than 2.5 mm. The parallel-plane geometry is normally used as electrodes in conventional DBD chamber. In this case, the electric field distribution between the plane electrodes is almost independent of the gap length. In the present experiment, we employed a needle-to-plane geometry as CCMD electrodes. In this case, the electric field is highly distorted especially around tip of needle.
The change of the gap length strongly affects the electric field distribution between the electrodes and also affects the discharge properties\(^{(18)}\). This dependency of the gap length on the electric field distribution is one of the reasons for the drastic change of the gap length strongly affects the discharge properties. The PMT output start to increase at only 2 ns after the applied voltage was 10.5 kVpp. The PMT output as a function of distance from needle tip to PMT measuring position from the needle tip.

Figure 10 shows that the CCMD current waveforms and the PMT outputs for three different measuring positions (\(C_q = 9.4 \text{ pF}, \ V_0 = 10.5 \text{ kVpp}, \ d = 5 \text{ mm}\) )

Figure 11 shows the time difference from discharge current start to PMT output as a function of distance of PMT measuring point from needle tip (\(C_q = 9.4 \text{ pF}, \ V_0 = 10.5 \text{ kVpp}, \ d = 5 \text{ mm}\) )

in Fig. 10. The each data was obtained by averaging via ten time measurements in order to reduce the scattering error. The velocity of the discharge development is roughly obtained to be \(3 \times 10^5 \text{ m/s}\). This value almost agrees with a streamer development speed in atmospheric pressure air\(^{(20)}\).

5. Conclusions

The characteristics of capacity coupled discharge in atmospheric pressure air were investigated with focusing influence of gap length of point-to-plane electrode configuration on input power into the discharge. The discharge was successfully quenched within 25 ns in duration according to 9.4 pF in a capacitance of the quenching capacitor. The discharge was classified as two modes; a spark mode and a corona mode. At the spark mode, the power consumed in the discharge plasma was almost 10 times as large as that of a conventional dielectric barrier discharge. At the corona mode, the consumed energy was almost same value with that of the dielectric barrier discharge. A velocity of the discharge development was obtained to be \(3 \times 10^5 \text{ m/s}\) by an optical measurement.

Acknowledgments

The authors thank S. Okazaki, Professor Emeritus of Sophia University, for her valuable discussion and comments. The authors thank N. Sato, Professor Emeritus of Iwate University, for his cooperation. This work was supported by a Grants-in-Aid for Scientific Research (JSPS Fellowship No. 1803001)

(Manuscript received July 10, 2006, revised Dec. 4, 2006)

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