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 experimental 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 k Ω . 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 μ F 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;

$$P = 2kfW_p = 2kf \left(\frac{R_p}{R_0 + R_p} \right) \frac{1}{2} C_q V_{BD}^2 \dots\dots\dots (1)$$

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

Fig. 1. Experimental setup for generation and measurement of capacity-coupled discharge (R_0 : damping resistor, C_q : quenching capacitor, C_L : capacitor for V - Q Lissajous measurement, C_0 : The capacitor for reducing the impedance of the power supply).

Fig. 2. Input power into the plasma as a function of applied voltage for two different gap lengths ($C_q = 9.4$ pF)

Fig. 3. Input power to the plasma as a function of gap length for two different quenching methods ($C_q = 9.4$ pF)

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 3×10^5 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 μ C, which corresponded to 70 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⁽⁶⁾.

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.

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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 k Ω . 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 nF 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 plasma was obtained from voltage-charge curves (V - Q Lissajous diagrams)⁽⁹⁾. Previously, the energies obtained from V - Q Lissajous diagram were confirmed to be correct by comparison with the values calculated from the time integral of the product of the applied voltage and the current. In this study, 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 inserted between the quenching capacitor and the ground. The discharge development was measured optically using a side-on type Photo Multiplier Tube (Hamamatsu Photonics 1P28).

Fig. 1. Experimental setup for generation and measurement of capacity-coupled discharge (R_0 : damping resistor, C_q : quenching capacitor, C_L : capacitor for V - Q Lissajous measurement, C_0 : capacitor for reducing impedance of the power supply)

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 kV_{pp} 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} ⁽⁵⁾. If we take 3 kV as the breakdown voltage V_{BD} , the integer k is calculated as 3 at applied voltages of 10.5 kV_{pp}, respectively, using following equation;

$$k = \text{Integer Part of } (V_{pp}/V_{BD}), \dots\dots\dots (1)$$

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 kV_{pp} 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 k Ω , 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

Fig. 2. Waveforms of drive electrode and capacity-coupled electrode potentials ($C_q = 1.0$ nF, $R_0 = 0$ Ω)

Fig. 3. Typical time-dependency of discharge current and electrode potentials (V_{CCE} : potential of CCE, V_0 : potential of high voltage electrode, $C_q = 9.4$ pF, $R_0 = 50$ k Ω)

Fig. 4. Waveform of the discharge current and the electrode potentials at 5mm gap length ($C_q = 9.4$ pF, $R_0 = 50$ k Ω)

Fig. 5. Typical V - Q Lissajous figure at gap length of 1 mm at 10 kV_{pp} applied voltage ($C_q = 9.4$ pF, $R_0 = 50$ k Ω)

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_{CCE} at 5 mm gap length. Other conditions are same as shown in Fig. 3. In this case of 5 mm gap, the pulsed 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 ΔV_{CCE} as $C_q \times \Delta V_{CCE}$ ($=9.4$ pF $\times$ 150 V). 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, $V_0 - V_{CCE}$, 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 pulsed discharge can be classified as a spark discharge; arc-like partially thermalized pulsed 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 kV_{pp}

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⁽²⁾.

Figure 6 shows that the V - Q Lissajous figure at 5 mm gap length and 10.0 kV_{pp} applied voltage. The capacitance of the quenching capacitor is set to be 9.4 pF. The discontinuous change of the charge 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 kV_{pp}. 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⁽⁶⁾. Here, the input power to the plasma P can be expressed by the following equation⁽⁵⁾;

$$P = 2kfW_p = 2kf \left(\frac{R_p}{R_0 + R_p} \right) \frac{1}{2} C_q V_{BD}^2, \dots \dots \dots (2)$$

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. Equation (2) implies that the input power P changes discretely under these experimental conditions, because all values of Eq. (2) are nearly constant except k , and the value of k can only be an integer. It is clearly seen from Fig. 7 that the input power increases discretely as the applied voltage increases of every 2 kV_{pp}. Moreover, the value of the input power increases about every 5mW, 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;

$$P_{DBD} = 4fC_g e_0 \left(e_m - \frac{C_a}{C} e_0 \right), \dots \dots \dots (3)$$

where $C = C_g C_a / (C_g + C_a)$, C_g and C_a are the capacitance of the dielectric and the capacitance of the air, respectively. e_0 is an applied voltage, e_m is a voltage between electrodes when there is no charge on the dielectric surface⁽⁹⁾⁽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_L 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

Fig. 6. Typical V - Q Lissajous figure at gap length of 5 mm at 10 kV_{pp} applied voltage ($C_q = 9.4$ pF, $R_0 = 50$ kΩ)

Fig. 7. Input power into the plasma as a function of applied voltage for two different gap lengths ($C_q = 9.4$ pF, $R_0 = 50$ kΩ)

Fig. 8. Typical V - Q Lissajous figure of DBD at 10 kV_{pp} applied voltage

Fig. 9. Input power to the plasma as a function of gap length for two different quenching methods ($C_q = 9.4$ pF, $R_0 = 50$ k Ω)

Fig. 10. CCMD discharge current waveforms and PMT outputs for three different measuring positions ($C_q = 9.4$ pF, $V_0 = 10.5$ kV_{pp}, $d = 5$ mm)

electrode⁽¹⁷⁾. 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 input power change between 2.0 and 2.5 mm in gap length.

4.2 Velocity of Discharge Development A velocity of the discharge development i.e. propagation speed of an ionizing wave can be measured using photo-multiplier tubes (PMT)⁽¹⁹⁾⁽²⁰⁾. Figure 10 shows that the CCMD current waveforms and the outputs of PMT from three different measuring positions of 0, 2 and 4 mm from the tip of the low voltage needle electrode. The gap length and the capacitance of quenching capacitor were set to be 5 mm and 9.4 pF, respectively. The applied voltage was 10.5 kV_{pp}. The PMT output start to increase at only 2 ns after the discharge current start to increase at measuring point near the needle tip (0 mm position). However, the time difference between the current and PMT output increases with increasing the distance of measuring position from the needle tip.

Figure 11 shows the time difference from discharge current start to PMT signal as a function of distance from needle tip to PMT measuring position. The experimental condition is same as shown

Fig. 11. Time difference from discharge current start to PMT output as a function of distance of PMT measuring point from needle tip ($C_q = 9.4$ pF, $V_0 = 10.5$ kV_{pp}, $d = 5$ 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 3×10^5 m/s from Fig. 11. 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 3×10^5 m/s by an optical measurement.

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