EFFECTS OF RISE RATE OF VOLTAGE IMPULSES ON OXYGEN-FED DIELECTRIC BARRIER DISCHARGES

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ABSTRACT

Dielectric barrier discharges (DBD) energised by voltage impulses with the rise rate of 300 V/ns and 500 V/ns have been investigated in the present work. A planar DBD reactor with a 0.5 mm gap distance was designed and developed. Experiment was carried out in oxygen at 0.02 bar gauge and ambient temperature of 20 ℃. The reduced electric field (*E/N*) in the discharge gap under impulse voltages with the two different rise rates was measured. A photomultiplier (PMT) was employed to detect the emitted light when discharges took place. The total current through the reactor was measured and the impulsive discharge current inside the discharge gap was calculated with the help of a one-dimensional DBD electrical model. The charge transferred through the gap during the discharge under both rise rates was also calculated. Results show that impulse voltages with the rise rate of 500 V/ns can provide *E/N* of 683 Td in the discharge gap, and 546 Td can be achieved with the rise rate of 300 V/ns. The charge transferred under the rise rate of 500 V/ns was ~213 nC, 2.1 times higher than the ~101 nC transferred with the rise rate of 300 V/ns.

1. INTRODUCTION

Dielectric barrier discharges (DBDs) are widely used for ozone production in different practical applications [1]. Ozone is produced through the dissociation of O_2 molecules by electrons and a subsequent three-body reaction of O atom, O_2 molecules and a third particle M [2]. Electrons in micro-discharges play a key role in ozone formation, as they produce the oxygen atoms necessary for ozone formation. Therefore, in order to optimize the ozone production efficiency, controlling the electron energy in the micro-discharges is important. It is known that the mean energy of electrons distributed in the gap is determined by the reduced electric field [*E/N*] in the gap [3]. Impulse voltage with fast rise rate permits the use of over-voltage across the discharge gap due to the time lag [4]. Hence higher *E/N* can be achieved under the impulse voltage energisation. The effect of *E/N* on the ozone generation efficiency and pulsed DBD for ozone generation has been studied by some researchers. Eliasson *et al.* demonstrated the dependence of ozone production efficiency on *E/N* through numerical calculations and showed that the optimum *E/N* for ozone production was from 100 Td to 200 Td [2]. Shuhai Liu *et al.* reported that the discharge onset voltage was about three times higher than the dc breakdown voltage under the square pulse with the rise time of 14 ns and the ozone synthesis efficiency was improved by 30% compared with sinusoidal excitation [5].

In the present paper, the effects of rise rate of voltage impulses on oxygen-fed dielectric barrier discharges are investigated. The reduced electric field and charge transferred inside the gap under both voltage rise rates of 300 V/ns and 500 V/ns is calculated. The effect of voltage impulses on ozone production is also discussed.

2. EXPERIMENTAL PROCEDURE

The DBD reactor used in the experiment has a planar electrode configuration. Its schematic diagram is shown in Fig. 1. Two stainless steel electrodes with the diameter of 30 mm were housed inside a sealed acrylic vessel and one of them was covered by a borosilicate glass with

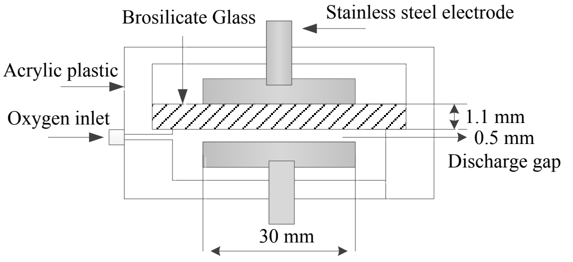

Fig 1. Schematic diagram of DBD reactor

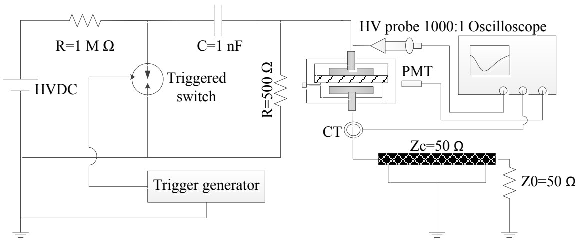

Fig. 2. Schematic diagram of electrical circuit

relative permittivity of 4.6 and thickness of 1.1 mm. A 0.5 mm discharge gap was formed between the glass and the grounding electrode. The reactor was vaccumized before the inlet of oxygen with the purity of 99.5% and the dew point of -40℃. The pressure of the gas inside the reactor was 0.02 bar gauge. The voltage across the gap before the occurrence of discharge, V_g, can be calculated from equation (1) as below. V_a is the applied voltage across the reactor. C_g and C_d are the equivalent capacitance of the gap and dielectric, respectively.

$$V_g/V_a = C_d/(C_d + C_g) \qquad (1)$$

The reduced electric field can be calculated as below:

$$E/N = V_g/(d_g \times N) \qquad (2)$$

where N is the gas density calculated from the ideal gas equation and d_g is the gap distance. The experimental circuit employed in the work is shown in Fig. 2. Negative voltage impulses were generated by charging a capacitor of 1 nF fed by a high voltage DC power supply via a 1 MΩ charging resistor. A 500 Ω resistor was connected in parallel with the DBD reactor. The grounding electrode of the reactor was connected to a 50 Ω matching resistor through a 50 Ω coaxial cable. A triggered switch, activated by a repetitive trigger generator, was used in the experiment, providing a pulse repetition rate of 50 pps. The rise time of the voltage impulse across the load is 40 ns. Two voltage impulses

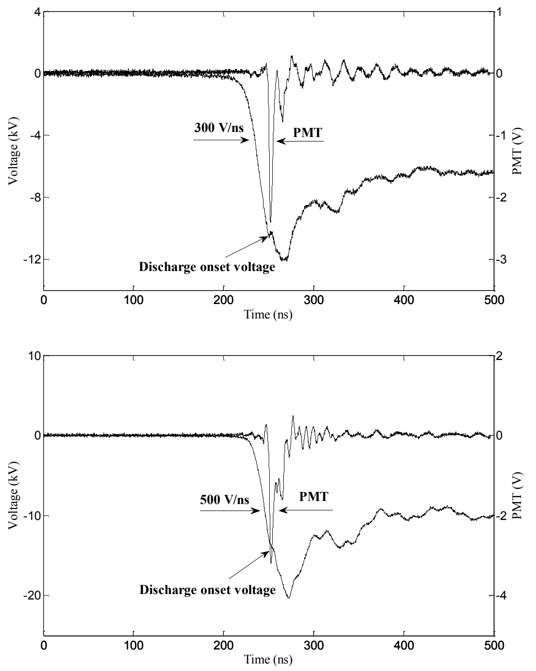

Fig. 3. Voltage impulses with 300 V/ns and 500 V/ns rise rates, and emitted light signal measured by PMT

with rise rates of 300 V/ns and 500 V/ns were generated by charging the DBD reactor to peak voltages of 12 kV and 20 kV, respectively. The voltage across the reactor was measured by a Tektronix P6015A high-voltage probe (bandwidth 75 MHz, division ratio 1000:1). The current through the reactor was measured by a fast current transformer (FCT) from Bergoz (bandwidth 32 kHz to 1 GHz). A Hamamatsu photomultiplier (H10721-01 with the rise time of 0.57 ns) was employed to detect the emitted light when discharges occurred. The voltage, current and emitted light signals were recorded by a Lecroy oscilloscope (Waverunner 610Zi, 1 GHz, 10 GS/s).

3. RESULTS AND DISCUSSION

3.1. Reduced electric field measurement

The voltage waveforms and corresponding PMT signals from discharges under both rise rates are shown in Fig. 3. The voltage and PMT signal were configured to arrive at the oscilloscope at the same time before the experiment. Therefore, from the occurrence of the PMT signal, the discharge onset voltage can be determined corresponding to the onset of the PMT signal. Twenty tests were carried out for each rise rate. The applied voltage when the discharges occurred are plotted in Fig. 4, which shows that the discharge onset voltage under both rises rates

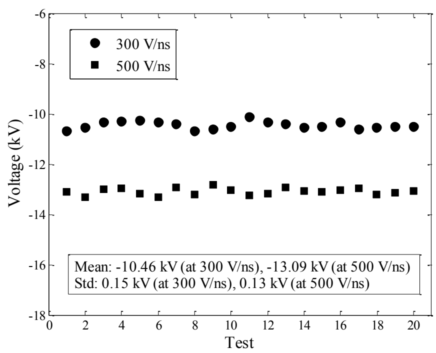

Fig 4. The applied voltage when the discharges occur under both voltage impulses with different rise rate

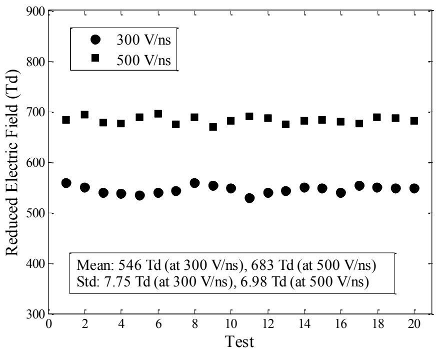

Fig. 5. The calculated reduced electric field under both voltage impulses with different rise rate

is inconsistent. This is due to the uncertainty of the statistical time lag associated with impulse breakdown of the gap. The mean value of twenty tests under the rise rate of 300 V/ns is -10.46 kV with the standard deviation of 0.15 kV, while the mean value under the rise rate of 500 V/ns is -13.09 kV with the standard deviation of 0.13 kV. According to equation (2), the *E/N* inside the gap can be calculated, and the results are plotted in Fig. 5. The results show that voltage impulses with the rise rate of 300 V/ns and 500 V/ns provide the *E/N* in the discharge gap with the mean value of 546 Td and 683 Td, respectively. The reduced electric field is improved by 25% under the rise rate of 500 V/ns compared with the rise rate of 300 V/ns. In our previous work [6], the *E/N* in the discharge gap during discharge under ac voltage with slow rise rate of 2 V/ns is 186 Td, increasing to 467 Td under impulse voltages with the rise rate of 120 V/ns. These results show that *E/N* increases by 2.5 times under impulses with the rise rate of 120 V/ns compared with the slow rising ac voltage, and that impulses with faster rise rate of 300 V/ns and 500 V/ns permit further increased E/N in the discharge gap.

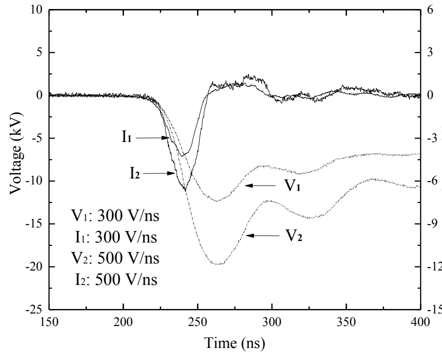

Fig. 6. The applied voltage and current through the DBD reactor when there is no discharge even

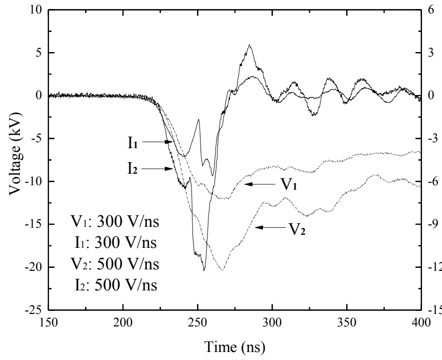

Fig. 7. The applied voltage and current through the DBD reactor when discharge even occurs

3.2. Discharge current and charge transferred measurement

Fig. 6 shows the voltage and current waveforms measured under different voltage rise rates when there was no occurrence of discharges. Because there was no discharge occurring in the gap, the DBD reactor is a pure capacitive load with capacitance of C_{DBD}, and the current waveform displayed in Fig. 6 is a purely capacitive current, $I_{c,a}(t)$. Fig.7 shows the waveforms measured when the discharges occur. It shows that the current increases sharply when the discharges occur. This results from the contribution from the motion of charged particles in the discharge gap to the total current measured in the external circuit, represented as $I_{p,a}(t)$. From the DBD electrical model proposed by Shuhai Liu [5], the total current $I_{t,a}(t)$ measured in the external circuit is:

$$I_{t,a}(\mathrm{t}) = C_{DBD}\frac{dV_a(t)}{dt} + \frac{I_{p,g}(t)}{1 + C_g/C_d} = I_{c,a}(t) + I_{p,a}(t) \qquad (3)$$

where $I_{p,g}(\mathrm{t})$ is the ohmic discharge current inside the discharge gap. The total capacitance of the reactor, C_{DBD}, is

$$C_{DBD} = C_g C_d / (C_g + C_d) \qquad (4)$$

$I_{p,g}$ can be calculated from equation (3) as below:

$$I_{p,g} = (I_{t,a} - I_{c,a}) \times (1 + C_g/C_d) \quad (5)$$

The discharge currents inside the gap were calculated and plotted in Fig. 8. Integrating the discharge current pulse (from 250 ns to 280 ns), the charge transferred from twenty tests can be calculated, and this data is plotted in Fig 9. The results show that the mean charge transferred under voltage rise rate of 500 V/ns is ~213 nC, 2.1 times higher than the ~101 nC transferred under the voltage rise rate of 300 V/ns. It can be explained that faster voltage rise rate provides higher *E/N*, hence more high energy electrons are generated, corresponding to the higher impulsive current shown in Fig. 8. More high energy electrons generated under higher *E/N* results in more oxygen dissociation and more oxygen atoms produced. However, the increased production of oxygen atoms does not translate to increased ozone production efficiency. Eliasson *et al*. reported that the ozone production efficiency dropped when the O atom concentration ([O]/[O_2]) was higher than 10^{-4} [2].

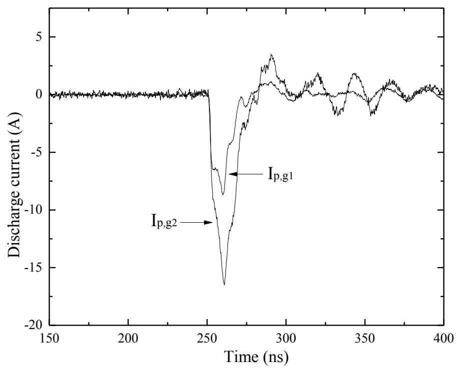

Fig. 8. The discharge current inside the discharge gap under the voltage rise rates of 300 V/ns and 500 V/ns respectively.

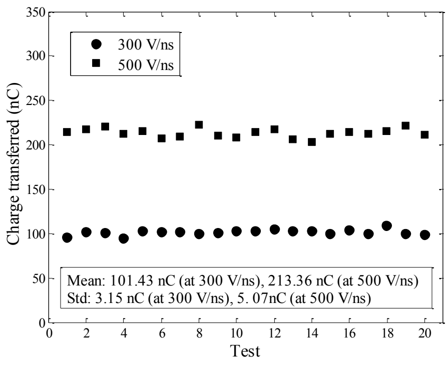

Fig.9. The charge transferred inside the gap

The ozone production efficiency may decrease rather than increase when discharges operate at higher *E/N*, explaining why the ozone production efficiency is lower under impulse voltage energisation than under ac energisation [6].

4. CONCLUSION

The effects of impulse voltage rise rate of 300 V/ns and 500 V/ns on oxygen-fed DBD were investigated. Higher *E/N* of 683 Td were achieved under the faster voltage rise rate of 500 V/ns, as compared with the *E/N* of 546 Td under the rise rate of 300 V/ns. *E/N* values achieved under both voltage rise rates are much higher than the breakdown *E/N* value for oxygen which is ~180 Td [7]. Effective ionisation of oxygen molecules is provided under these significant *E/N* values. The charge transferred under the higher rise rate is increased by 2.1 times compared with the lower rise rate.

REFERENCES

[1] U. Kogelschatz, "Dielectric-Barrier Discharges: Their History, Discharge Physics, and Industrial Applications," *Plasma Chemistry and Plasma Processing*, vol. 23, pp. 1-46, 2003.

[2] B. Eliasson, M. Hirth, and U. Kogelschatz, "Ozone synthesis from oxygen in dielectric barrier discharges," *J. Phys. D: Appl. Phys*, vol. 20, pp. 1421-1437, 1987.

[3] L. B. Loeb, *Fundamental Processes of Electrical Discharge in Gases*, New York, John Wiley & Sons, Inc, 1939.

[4] E. Kuffel, W. S. Zaengl, J. Kuffel, *High Voltage Engineering: Fundamentals*, Newnes, 2000.

[5] S. H. Liu and M. Neiger, "Excitation of dielectric barrier discharges by unipolar submicrosecond square pulses," *J. Phys. D: Appl. Phys*,vol. 34, pp. 1632-1638, 2001.

[6] G. M. Huang, T. Wang, I. V. Timoshkin, S. J. MacGregor, M. J. Given, M. P. Wilsion, "A comparative study of ozone production using pulsed and continous ac dielctric barrier discharges", presented in the *19th IEEE Pulsed Power Conference*, San Francisco, CA, USA, 2013.

[7] D T A Blair and H W Whittington, "Ionization and breakdown in oxygen," *J. Phys. D: Appl. Phys*, vol. 8, pp. 405-414, 1975.