Decay time of Current Pulse by Disruption of Taylor-cone Formed at a Capillary Electrode under DC Field

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***Abstract*—Since a water droplet extruded at a tip of a capillary tube under a strong dc electric field repeats formation of a Taylor cone and ejection of fine drop jet due to partial disruption of the cone, the current waveform consists of the largest first pulse resulting from an ejection of fine droplets and successive negative corona pulse trains. Charge quantity and decay time of current pulse was analyzed to confirm the effect of the presence of space charge or the charged droplet. The first pulse stemming from disruption of the tip of the cone has the largest peak and largest charge quantity. The decay time of the current pulse was much larger than that of successive corona pulses and strongly depends on the .conductivity of the water droplet.**

I. INTRODUCTION

A water droplet extruded at a tip of a capillary tube with negative polarity under a dc electric field forms a Taylor cone and ejects fine drops due to partial disruption of the cone [1, 2]. The process of cone formation and disruption occurs repeatedly and periodic vibration of the water droplet causes due to resonant vibration [3, 4]. During a single vibration of the droplet with negative polarity, the current waveform due to periodical disruption or droplets ejection manifests a series of corona pulse trains subsequent to the largest first pulse [5]. In such a situation, corona discharge involves with ejection of nanometer-sized droplets as well as negative ions and ozone [6, 7]. Consequently, current pulses due to corona discharge was superimposed to that by disruption of the Taylor cone.

The waveform of current pulse would have key information on generation and dispersion of charged particles existing between the tip of a water droplet and a counter electrode. Especially, conductivity of water droplet affects the number of nanometer-size fine droplet. The higher conductivity, the smaller and more droplet was produced [7]. Therefore, the current waveform might give a hint to explain the reason for the dependence of conductivity.

In this paper, to clarify the event at disruption of a Taylor cone, the waveform of current flowing through a water droplet formed at a tip of a capillary tube with a diameter of 180 μm were analyzed focusing on decay time of individual current pulses. The first pulse

occurring at breakup of the Taylor cone would contain information on charge quantity and the number of negatively charged fine droplets while the successive pulses due to corona discharge would produce negative ions. The charge quantity borne by each droplet ejected at immediately after disruption would depend on the field strength at the cone tip and charge quantity concentrated near the tip at disruption. Since these charged droplets or ions produced in a current pulse form a space charge cloud, thus they would affects the electric field strength at the tip of the water droplet, thereby the decay time of the current pulses. Relationship between decay time of the current pulse and the conductivity of sample water was shown. The influence of conductivity on ejected charge or dispersion process was also investigated.

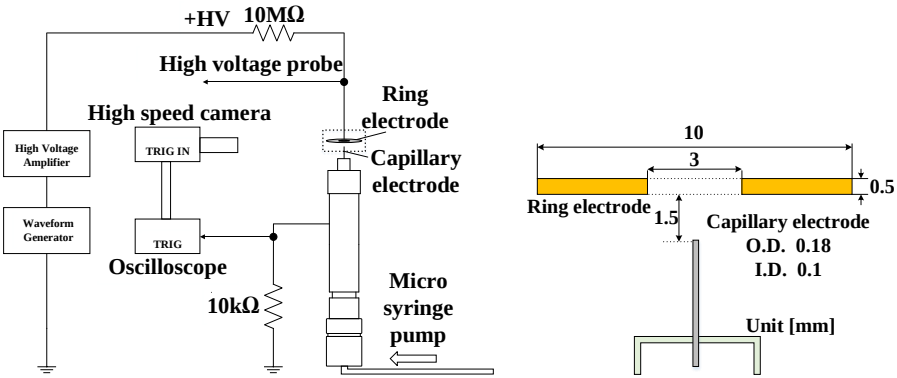
II. METHOD

A. Measurement of current waveform

To observe corona discharge from a water droplet, a capillary and a ring electrode was used. Fig. 1 shows schematic diagram for measuring corona discharge current. By applying the positive voltage to the ring electrode, negative corona discharge occurs from the droplet. The capillary electrode with 0.1mm inner and 0.18mm outer diameter was set upwards in vertical direction. The counter ring electrode with an inner diameter of 3 mm and a thickness of 0.5 mm was set at a distance of 1.5 mm.

A water droplet was formed at the tip of the capillary tube where sample water was fed by a syringe pump (kd-Scientific, kds-100) with a flow rate of 8.3μL/h. Through the experiments, the water temperature was kept at 25 °C to make surface tension or viscosity of sample water keep constant. The conductivity of sample water was varied from 0.003 to 48 mS/cm by adjusting the concentration of the nitric acid water solution in deionized water.

The waveform of corona current flowing through the capillary electrode was measured by a register of 10 kΩ and a digital oscilloscope (Tektronix, TDS 5104B, 1 GHz, 5 GS/s). Since the input impedance of the oscilloscope is 100 MΩ and 18 pF, the time constant of



(a) Current measuring system (b) Configuration of a capillary and ring electrode system.

Fig. 1. Experimental setup for measuring current waveform flowing through a water droplet extruded from a tip of capillary electrode.

the whole current measuring system is around 180 ns. The motion of a water droplet was taken with a high-speed video camera (Photoron, Mini AZ) at a speed of 40,500 frames/s synchronized with the oscilloscope.

B. Analysis of a waveform of current pulse

To obtain charge quantity of current pulse and decay time of individual pulse generated by disruption of a Taylor cone as well as subsequent corona discharge, the current waveform was measured with a sampling of 100,000 data per single sweep at a time scale of 2ms. This means one sampling was logged by 20 ns.

Since the first pulse by disruption of the cone was superimposed by the subsequent corona pulses, it is difficult to obtain the charge quantity of the first pulse by operation of time integration of the current waveform. Therefore, the charge quantity was obtained by products of the peak current and decay time constant as follows: Assuming every pulse decays exponentially, the decay time constant τ is defined as the time when the peak value I_p decrease to 1/e of peak value. Since the charge quantity q of a single pulse is derived by integration of the exponential function with a peak value I_p and time constant τ from zero to infinite, the charge quantity q is expressed by the product of the decay time and the peak value, that is, $q = \tau I_p$. In this paper, decay constant was referred to decay time not fall time.

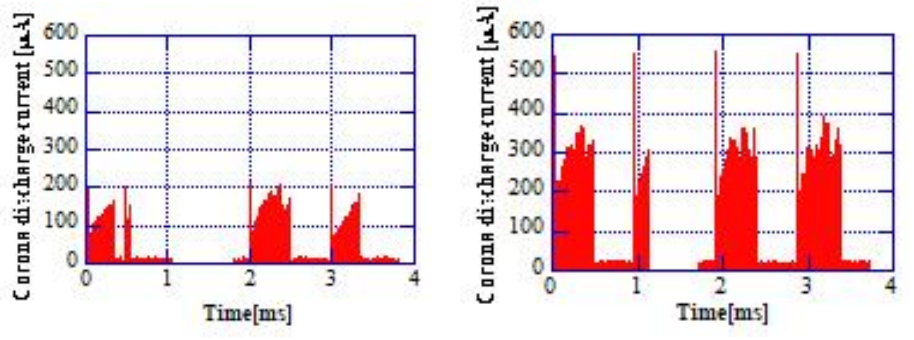
III. Results and Discussion

A. Current waveform during disruption process of Taylor cone

Fig. 2 shows typical current waveforms of negative corona discharge occurring at a nitric acid water droplet with a conductivity of 0.48 and 48 mS/cm, when dc positive voltage with 2.32 kV was applied to the ring electrode. Time 0 indicates triggering position of the oscilloscope. In Fig. 2, there is a lack of data between 1-2 ms, because of dead time between the successive records.

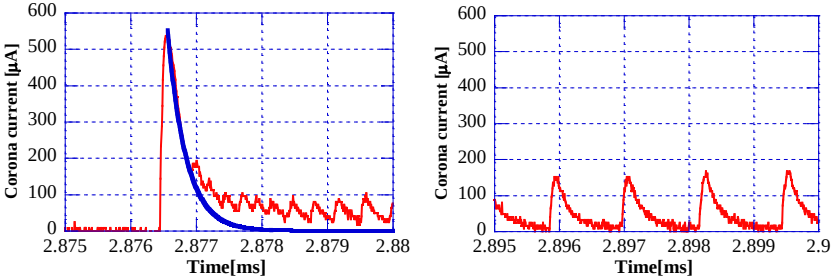
Corona discharge occurs periodically with a height of the first pulse with about 200 and 500 μA. The droplet repeats formation of a sharpened cone and the returning to a round droplet at almost regular period. A series of pulse trains with the largest first pulse corresponds to the disruption of a Taylor cone and the following pulses do to successive corona discharge. After the tip of a Taylor cone breaks into a number of fine charged jets, the cone returns to the round shape to the lower height. Time variation in shape of the droplet during the upward and downward motion of the tip of a droplet is consistent with the magnitude of the corona pulse trains.

Fig. 3 shows an enlarged waveform of the fourth pulse group in Fig 2(b) at time of around 2.87 ms and 2.89 ms where the time axis of abscissa corresponds to that shown in Fig. 2(b). The first pulse and subsequent pulses decays exponentially. An exponential line was drawn on the current waveform in Fig. 3(a). After the first pulse appeared at 2.8765 ms, the successive corona pulse trains followed during the decay of the first pulse. These corona discharge occurred because the water droplet kept sharp shape for a while even after partial disruption of the tip of the initial Taylor cone. The height of successive corona pulses increased gradually. During the period increase of the pulse height, the droplet shape return to the lower round shape. As the successive pulse height increases, the electric field strength decreased gradually. This pulse characteristics resembles Trichel pulse of negative



(a) 0.48 mS/cm (b) 48 mS/cm.

Fig. 2. Current waveform appeared when Taylor cone is formed and breakup repeatedly at the tip of the water droplet extruded from a negative capillary electrode: Conductivity of the sample water



(a) First pulse by disruption (b) Successive corona pulse

Fig. 3. Enlarged waveform of the first pulse for disruption of the cone. The repetitive pulses during the decay shows corona discharge occurred in resembled to Torricelli pulse.

corona discharge from metal electrode.

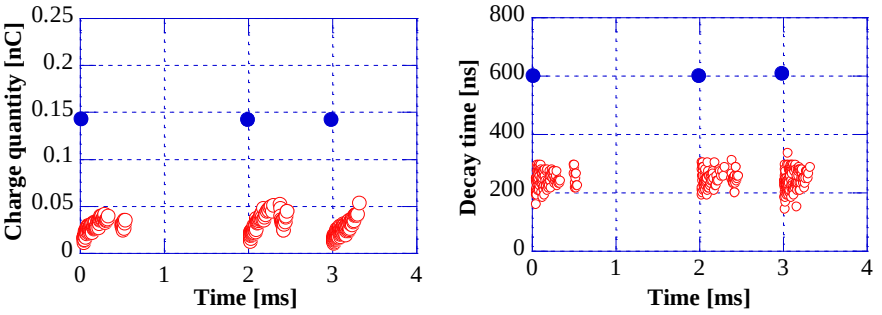
B. Decay time of current pulse

The waveform of individual current pulse waveform indicates the generation and transition of charge; disruption of a Taylor cone or ejection of charged droplets, successive pulse trains due to corona discharge from the water electrode, and dispersion of negatively charged droplet and ions towards a counter electrode or space. Regular repetition of the corona pulses manifests the time variation of the electric field strength at the tip or the vicinity of the electrode. Negative corona discharge generates some charges in forms of ions, while disruption of Taylor cone emits a number of charged fine droplets. The electric field strength at the cone tip decreases temporarily by the presence of the ions or charge droplets near the tip of the electrode. Dispersion of the charged particles near the droplet must recover the electric field strength. The slower dispersion, the longer decay time.

Fig. 4 shows the time variation of charge quantity and decay time of each current pulse for the conductivity of water droplet with 0.48 μS/cm. Since the first pulse in each pulse group or disruption of a Taylor cone has the largest peak and charge quantity emitted by the first pulse ranges 0.13 to 0.14nC. The charge quantity of successive pulses reaches to

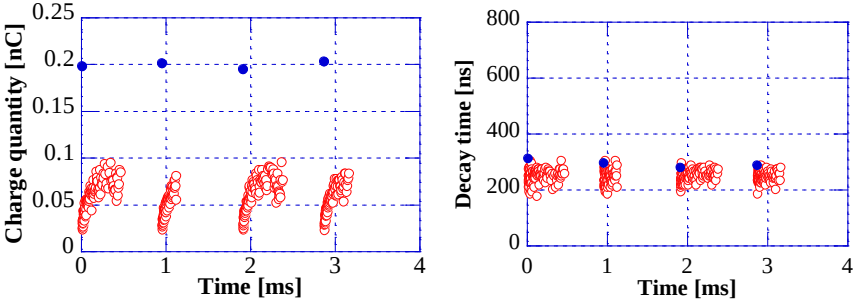
0.05 nC at most. There is large difference between the first pulse due to ejection of droplet jet and following corona pulses. Decay time of the first pulse was around 650ns, while that of the successive pulses ranges from 180 to 300 ns. On the other hand, as shown in Fig. 5 for the conductivity of the water sample of 48 mS/cm, charge quantity of the first pulse and the successive pulses are 0.2 and below 0.1 nC, respectively. The decay time of the first pulse is larger than that of successive corona pulses, but they are within almost the same time range of 200 to 300 ns. Fall time of Trichel pulse from a metal needle electrode has been reported as 400 ns [8], where the decay time would be around 100 ns. This difference would stem from a detection resister. Decay time of the measured pulse is governed mainly by time constant of the measuring circuit as well as dispersion time of space charge. As shown in Fig. 6, the charge quantity carried by current pulse increased with peak current. The higher conductivity of a droplet, and the larger first pulse appeared. The larger pulse would result from generation of the more number of charged droplets.

As shown in Fig.7, decay time of the first current pulse due to cone disruption for 0.003 and 48mS/cm is around 600 and 300 ns, respectively, while that of successive corona pulse ranges 200 to 300 ns, regardless of conductivity, as shown in Fig.4 and Fig. 5. The dependence of water conductivity could be explained by the size of produced charged droplet. Fig. 8 from Ref[7] shows the higher conductivity, the smaller and more number



(a) Charge quantity (b) Decay time

Fig. 4. Charge quantity and decay time of current pulse for sample water with conductivity of 0.48mS/cm.



(a) Charge quantity (b) Decay time

Fig. 5. Charge quantity and decay time of current pulse for sample water with conductivity of 48 mS/cm.

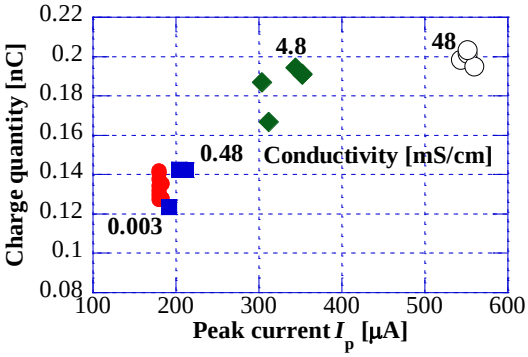


Fig 6. Relationship between the current peak and charge quantity of the first current pulse.

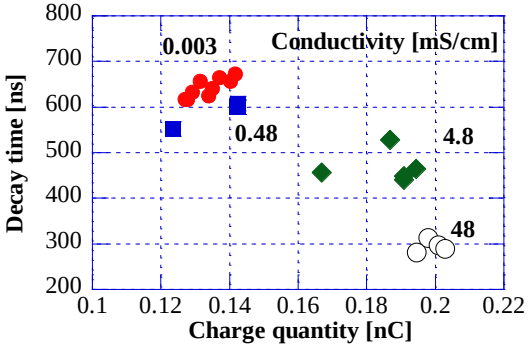


Fig. 7. Relationship between the charge quantity and decay time of the first current pulse generated by disruption of the Taylor cone.

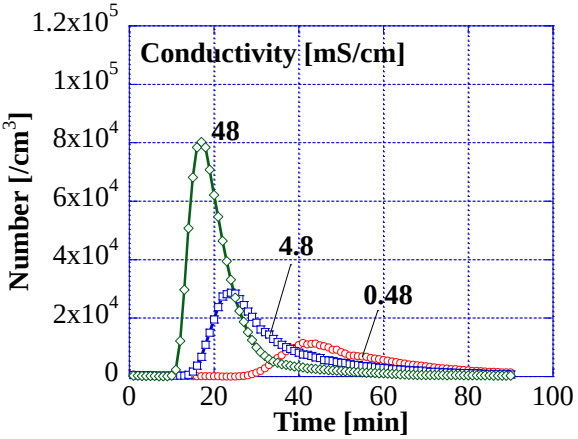
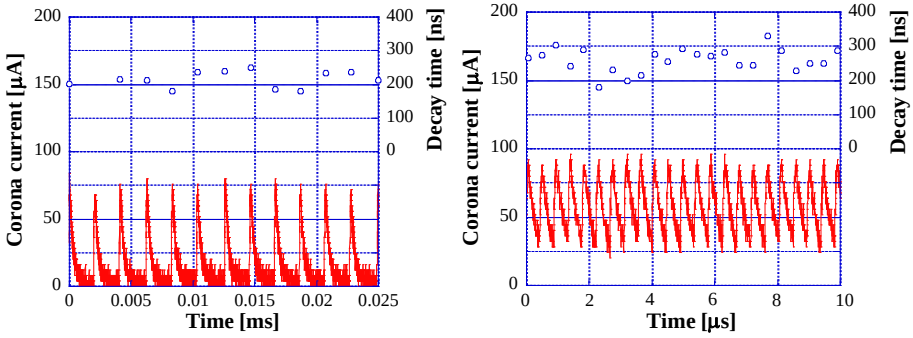


Fig. 8. Time variation of the number of 11.5~20.5 nm water droplets produced during negative corona discharge from a conductive water droplet from the reference [7].

of fine droplets. Dispersion due to electrostatic repulsion and mobility of the negatively charged particles depend on the charge quantity and droplet size. Thus the decay time of current pulse due to disruption of the Taylor cone would depend on the conductivity of the water droplet..

C. Comparison with current waveform from a metal electrode

To compare the decay time of current pulse by cone disruption with that of corona current from a metal electrode, corona current was measured using a needle electrode with a radius curvature of 35 μm. The electrode setup was same to the configuration shown in Fig. 1(b). Fig. 9 shows typical Trichel pulses with almost constant peak current and regular interval period. The peak value from the metal electrode was smaller than that from a water electrode, since the water electrode could elongate. The decay time ranges mainly from 200 to 300 ns. The decay time is almost same to the successive corona pulse from a water droplet.



(a) Applied voltage 1.74 kV (b) Applied voltage 2.38 kV

Fig. 9. Trichel pulse from a negatively needle electrode with a radius curvature of 35 μm for the applied voltage to a ring electrode.

REFERENCES

[1] G. Taylor, Disintegration of water drops in an electric field, Proc. R. Soc. London, A280, pp.383-397, 1964
[2] Y. Higashiyama, T. Shiori: Negative Corona Discharge from a Water Droplet with or without Resonant Vibration, Int. Symp. on Electrohydrodynamics, ISEHD 2012, Gdańsk, Poland (2012)
[3] M. Strani and Sabata, "Free vibration of a drop in partial contact with a solid support", J. Fluid Mech. Vol. 141, pp. 233-247, 1984
[4] T. Tsukada, M. Sato, N. Imaishi, M. Hozawa, K. Fujinawa, "A theoretical and experimental study on the oscillation of a hanging drop", J. Chemical Engineering of Japan, vol. 20, no. 1, pp88-93, 1987
[5] T. Sugimoto K. Asano, and Y. Higashiyama, "Negative Corona Discharge at a tip of a water cone deformed under dc field", J. Electrostatics, vol. 53, pp. 25-38(2001).
[6] H. Suda, N. Iwamoto, Y. Matsui, T. Yamauchi, K. Okuyama, "The study of application using electrostatic atomization", Proc. Annual Meeting of Inst. of Electrostatics Japan, 12pB-5 (2003) pp.237-238
[7] Y. Higashiyama, T. Nakajima, T. Sugimoto: Influence of conductivity on corona discharge current from a water droplet and on ejection of nano-sized droplets, J. Electrostatics(2017), http://dx.doi.org/10.1016/j.elstat.2017.01.022
[8] P. Dordizaden, K. adamiak, G. S. P. Castle, "Experimental study of the characteristics of Trichel pulses in the needle-plane negative corona discharge in atmospheric air, J. Electrostatics, 88(2017) 49-54