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ABSTRACT

The demand for high-efficiency dust collectors has rapidly increased to remove particulate matter (PM) from exhaust gas emission facilities, such as thermal power plants, steel mills, and industrial cogeneration plants, as the permission standards have been strengthened. Electrospray gas treatment technology is a promising method due to high-performance for PM removal and low water consumption rather than scrubbers and wet ESP. It is an atomization technique that only requires DC voltage and negligible pressure/pumping power to maintain the spray. The spray conditions of electroscrubbers have been studied are not suitable to treat the actual exhaust gas. For dust removal, the flow rate over 10 mL/min per nozzle is required, which ranges hundreds of times in typical electrospray fields. The electrospray of high flow rate has a completely different spray shape from the low flow rate condition, and it was visualized through various figures such as corona discharge photographs and shadow images. The corona discharge caused by the high-electric field strength can increase the removal efficiency of charged dust particles, and the removal efficiency was expected to be high as the corona discharge current increased with the high-applied voltage, flow rate, and electrical conductivity of the liquids. However, at voltages above a certain range, spark discharges occurred and proceed to arc discharge (short circuits). As a result of the PM removal performance evaluation based on optimal operating conditions derived from the experiments, the removal efficiency of PM10 was 99.65%, PM2.5 was 97.59%, and PM1.0 was 90.95%. Through this study, it has the potential to be practical reference for the electroscrubber in actual plants.

Keywords: Electrospray, electroscrubber, Particulate Matter, Corona discharge, Visualization

1. INTRODUCTION

For highly effective exhaust gas treatment, scrubbers have been used widely in industries. They tend to consume a lot of energies and water to remove submicron particles. Even spray type scrubber, high hydraulic pressure is required to atomize the water in the nozzle. Electroscrubbers have been proposed for many years to solve this problem of submicron particles removal. However, only a few studies reported and the main issue regarding water consumption and filtering of contaminated water remain unsolved. This content is based on configuration of arranging multi nozzles for electrospray in a cyclone scrubber. In the cyclone electrospray scrubber, large and heavy particles over 100 μm such as fly ash and coal dust can be removed by centrifugal force and gravity through the cyclone. On the other hand, the smaller and lighter ones such as PM10 which are floating inside cyclone can be treated by electrospray. They collide with charged droplets from electrospray, and flow down. The clean gas is emitted to the center pipe outlet. Electrospray can easily make droplets by electrical force without pressure and pumping power to maintain spray. Because the droplets are charged, they also collect the light particles by electrical attraction, not only inertial force. So, high efficiency for particle removal is achieved with very little water.
This content purposes to observe the shape of water electrospray for dust particles removal according to voltage, mass flowrate, and electrical conductivity of liquid (Mora and Loscertale, 1994). The flowrate set this study is very less than the water used in general spray scrubber, but it is at least tens of times larger than that in conventional

water electrospray field (Lopez-Herrera *et al*., 2004). Also, the spray shape in electrospray is easily changed by parameters such as applied voltage, flowrate, conductivity, etc., so it is essential to visualize the spray mode for use in scrubber. This study also includes discharge current experiment. In fact, there is a technical limit to measure the amount of charge of droplets in mid-air. By observing the discharge current of the dust collecting plate and comparing according to electrical conductivities of liquid, the charge of droplets was estimated. As a result, in general, the higher the electrical conductivity, the more charge the droplet has, but it is thought that there is a limit above a certain level.
Fig. 1. represents how the particles removed. When the liquid is passing through negatively charged nozzle, it is also be negatively charged. Ejected liquid is dispersed into droplets by repulsive force. They collide with charged PM particles inertially and inductively. At last, they are removed by cleansing water at the collecting electrode.

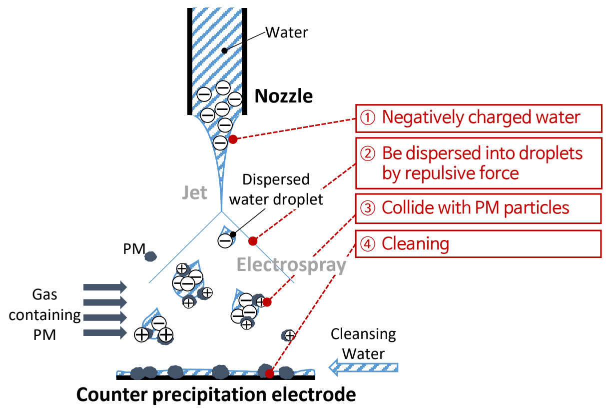

Figure 1: Mechanism of PMs removal with electrospray

2. EXPERIMENT ON WATER ELECTROSPRAY

2.1 Experimental apparatus

An experimental set-up of electrospray with single unit nozzle is illustrated in Fig. 2. Water passing through the negatively charged metal nozzle receives electric charges. That is located on the surface of the liquid and atomize to droplets due to electrical repulsive force. The droplets move toward the ground plate and the current flowing through a resistor is measured by oscilloscope. Spray shape of water is visualized using DSLR camera with strobe light source that has very short flash time. Behaviors of the droplets and jet which means water stream near the nozzle tip can be observed. Electricity shielding is the most important thing for accuracy of current measurement and safety against current leakage in designing the experiment. Because the leakage impinges on the electrical device, spraying system is surrounded by sub-conductor, insulation glass tub, and the capillary support that held the needle is composed of Teflon and acrylic.

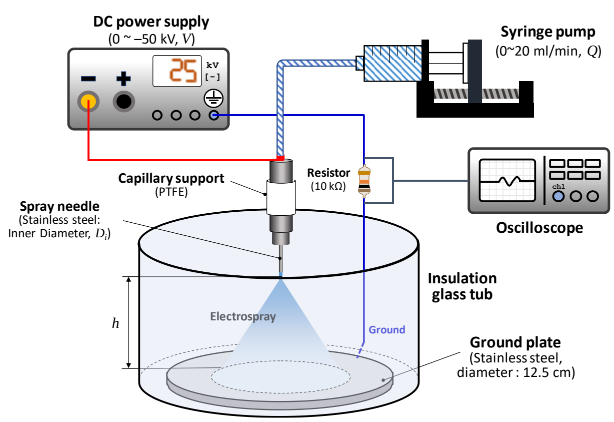

Figure 2: Schematic diagram of experiment on water electrospray

Table 1 summarizes experimental conditions. Applied voltage ranges from 0 to -50 kV with a minimum step of 1 kV. Volumetric flow rate of water is set in range of 1-20 mL/min to observe all the spray shape and current characteristics well. In this study, when voltage was just applied to the metal needle without injecting a liquid, it was referred to as a "dry condition". To presume the effect of the current generated by electrospray on corona discharge, a comparison of the discharge characteristics between in electrospraying condition and in dry condition was performed.

Table 1: Experimental conditions of spray in this study

Applied voltage [–kV]	Volumetric flow rate [mL/min]	Needle diameter [mm]	Distance from needle to plate [mm]	Diameter of plate [mm]
0–50	0 (dry) 1–20 (wet)	0.67 (inner) 1.07 (outer)	50	120

2.2 Modes of water electrospray

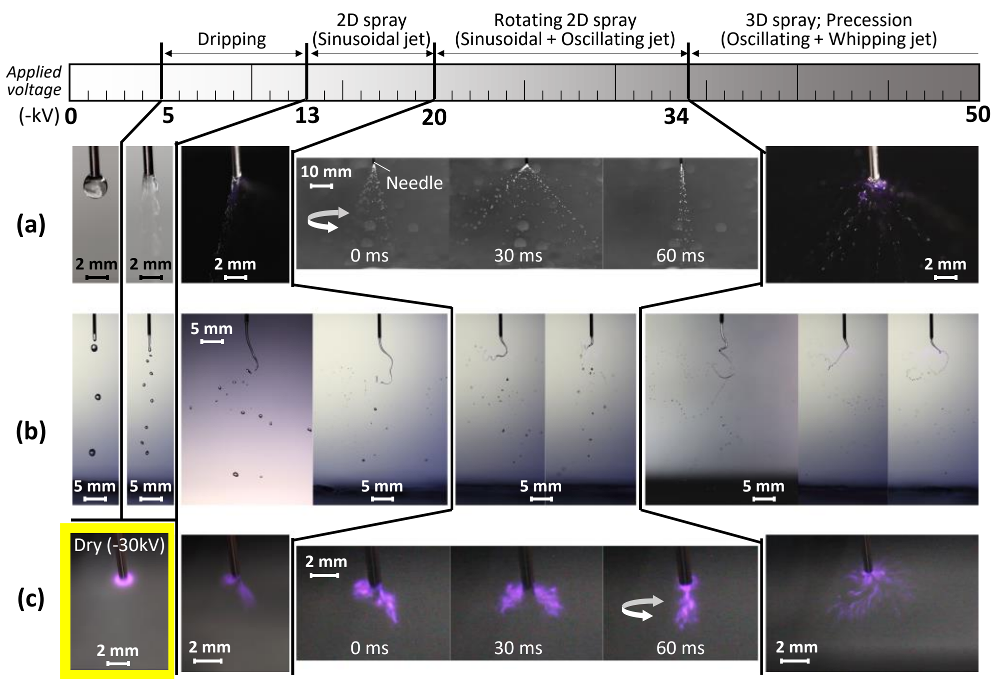

Figure 3: Electrospray mode classification (tap water, Q = 10 mL/min, V = 0 to −50 kV).
(a) Trajectories of droplets; (b) Snapshots of electrospray; (c) Corona discharge

In Fig. 3, the electrospray modes are classified according to the applied voltage increasing in a single nozzle. The right side indicates the high voltage, and the flowrate of tap water is 10 mL/min to observe the variation of spray shape clearly. Fig. 3 (a) is images of trajectories of the droplets. It seems what we actually see. Fig. 3 (b) is the images with the short light exposure time to closely observe the changing droplets and jets (Kim *et al*., 2014). Fig. 3 (c) shows the corona discharge. The occurrence of corona can be observed with eyes from the electrode or water surface, because when the secondary electrons are emitted from the electrode surface (the progress of corona discharge), and they pop out with the photoelectrons which glowing with purple. The most prominent characteristics of water electrospray under flowrate condition in this paper is appearance of two- and three-dimensional (2D, 3D) spatial distribution sprays because of its high surface tension. These features are appeared in limited high flow rate over 5 mL/min, and the glow discharge is dominant in the low flow rate of water electrospray (Borra *et al*., 2004). When the voltage is getting higher, the droplets are accelerated, and jet which is the liquid flowed out form the tip of nozzle. It also make the droplets be smaller (Kim *et al.*, 2011). The droplets and jet are seemed like a sinuous wave and the spray looks like a two-dimensional plane as shown in -13~20 kV. The voltage is getting over -20 kV, distortion causes the jet to oscillate. It causes the jet to rotate around the axis of the needle. When over -34 kV, the jet starts to be whipping forming a helix and looks like a 3D cone shape. It is expected that the PM removal effect will be best at 3D mode which has a wide spray range, so the probability of collision between submicron particles and droplets increases.

2.3 Discharge of electrospray according to liquid electrical conductivity

The mechanism of negative corona discharge under the conventional dry needle condition and electrospray is illustrated in Fig. 4. The negative corona discharge is described by Chen and Davidson (2003) in Fig. 4 (a). The corona discharge appears when potential difference between electrodes exceeds the dielectric strength of the surrounding air, which become ionized (Jaworek and Krupa, 1997). electrons existed between the electrodes are accelerated by electric field and generate positive ions from neutral gas molecules by inelastic collision. The positive ions also become energetic, and they collide with the surface of the negatively charged needle. Simultaneously, secondary electrons are released, move to ground plate, and are measured as current at the plate. On the other hand, during electrospray, the secondary electrons are extracted from the surface of liquid not the needle. It means that the liquid surface is charged, and the purple light originates from the liquid surface like Fig. 3 (c). In this situation, droplets carry the electric charges to ground plate.

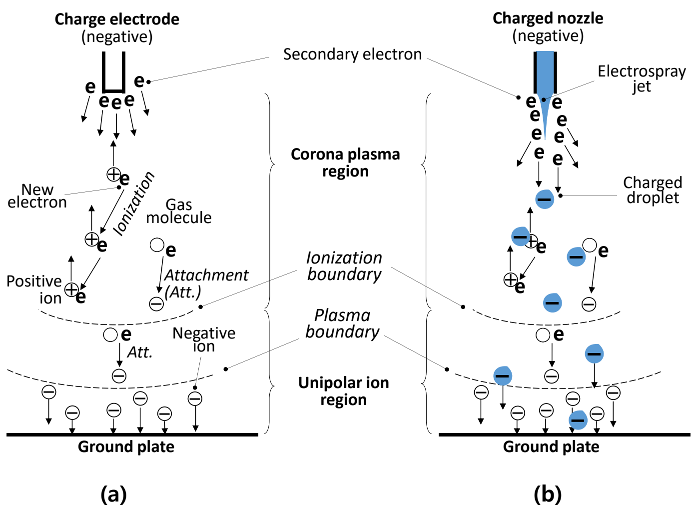

Figure 4: Mechanism of negative corona discharge. (a) dry condition (Chen and Davidson); (b) electrospray

Table 2 summarizes the properties of NaCl aqueous solutions to test the effect on the electrical conductivity of liquids. There are some studies about electrical conductivity of liquid, but they are much lower range than this study (Yazdekhsti *et al*., 2019). The flowrate is limited until the spark discharge occurs. The power consumption can be estimated from the measured current and the average applied voltage.

Table 1: Properties of working fluids according to electrical conductivity in this study

Fluid	Temperature [°C]	Salinity [%]	Electrical conductivity [mS/cm]	Flow rate (at –34 kV) [mL/min]	Applied voltage (at 10 mL/min) [–kV]
distilled water	25	-	-	1–20	0–50
tap water		0.10	0.25 ± 0.01		
saline solution		0.85	14.05 ± 0.05	1–16	0–40

Fig. 5 shows the current-voltage (*I*-*V*) curves at a flowrate of 15 mL/min for three liquids. The corona current increases via a quadratic function as the applied voltage increased by the Townsend avalanche (Townsend, 1914). As the charged droplets transfer the electric charge to ground plate during the electrospray, the current is larger than dry condition (black line). The liquid which has the higher electrical conductivity transfers more charge and that of current is higher (Smith, 1986). *Spark over* is occur when the potential difference between the electrodes is over the certain range. It refers to the point at which spark discharge begins. However, since the distilled water has very low conductivity (~0.003 mS/cm), the applied voltage just atomizes liquid into droplets, and the generated droplets are hardly charged. Electron charges are released less at surface of liquid than at metal needle. That's why the current of distilled water is lower than the dry condition.

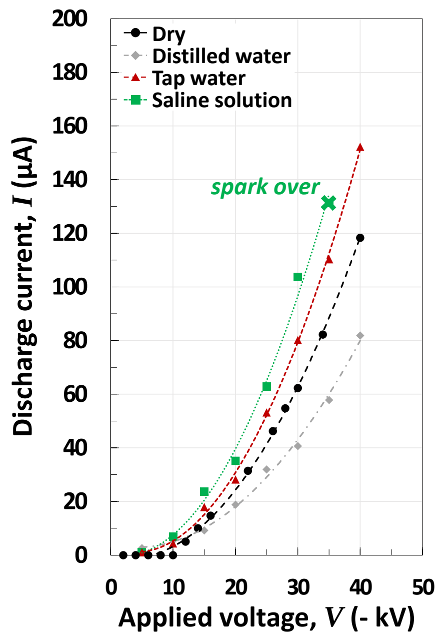

Figure 5: I–V characteristics of the electrospray with electrical conductivity (Q = 15 mL/min).

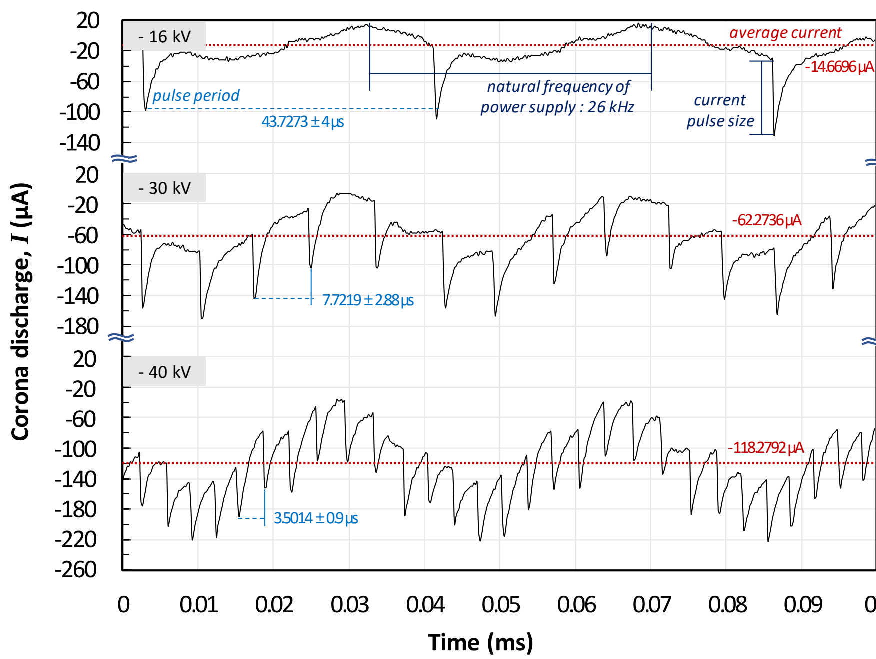

Figure 6: Waveforms of corona discharge with Trichel pulses.

Fig. 6 is the waveforms of corona discharge at -16, 30, and 40 kV in the dry condition. Corona discharge is a phenomenon in which secondary electrons drift out through the locally conductive air, as explained earlier. The emission of electrons appears as a current pulse called as Trichel pulse (Trichel, 1938), and it represents a certain frequency. The frequency of Trichel pulse is getting higher with voltage increasing, and it develops to spark or arc discharge which can make melt the needle. This is shown in Fig. 7.

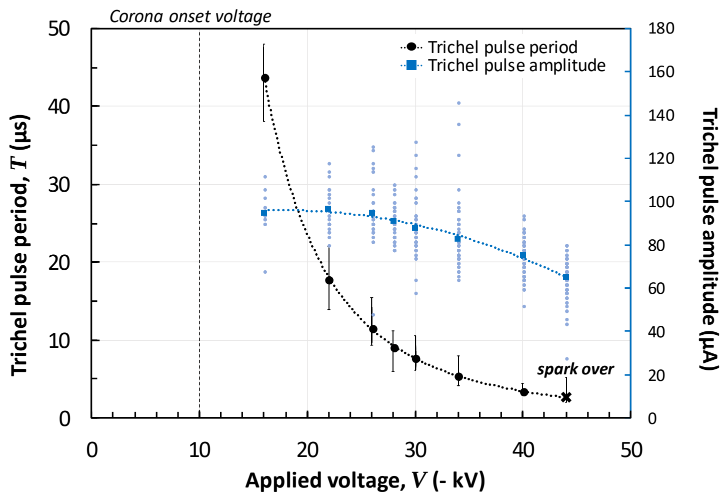

Figure 7: Trichel pulse period and amplitude with voltage increasing in dry condition

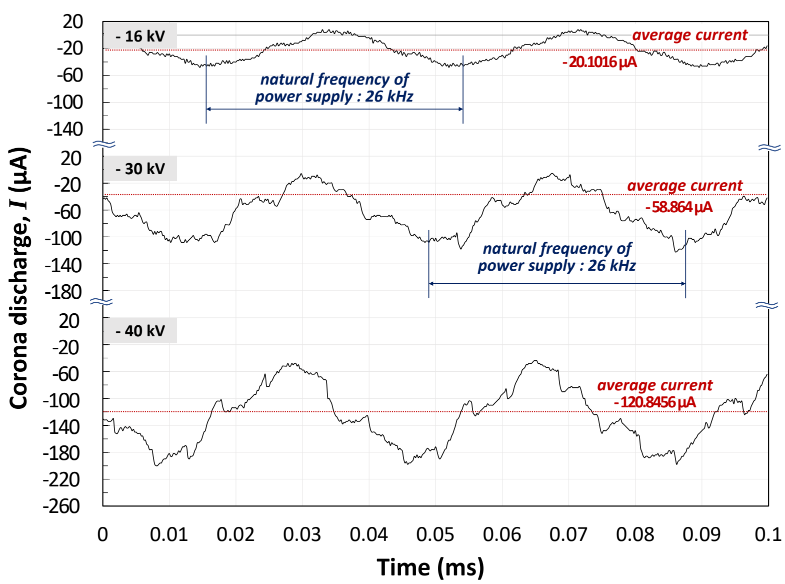

Figure 8: Waveforms of discharge current with tap water electrospray (Q = 10 mL/min).

Fig. 8 is the waveforms of tap water electrospray when voltages of -16, 30, and 40 kV are applied for 0.1ms. There is a vibration at 26 kHz in a few mV of amplitude that represents natural frequency of DC power supply. The more voltage is applied, the more average discharge current flows. Because the flow of charged droplets compensate for the potential difference between the electrodes, Trichel pulse that feature of negative corona discharge in dry condition is not appear. The Trichel pulse is that a large amount of charge is poured out instantaneously to relieve the electric field in the air as it increases. Under a fixed voltage, a current of constant magnitude appears with a constant period, and the greater the voltage, the shorter the period. However, in the case of distilled water, its droplets have few charges, and strength of electric field is continuously getting larger. So, the Trichel pulses appear which is shown in Fig. 9 and the amplitude and period of pulse at this point followed a random nature because of randomly generated droplets.

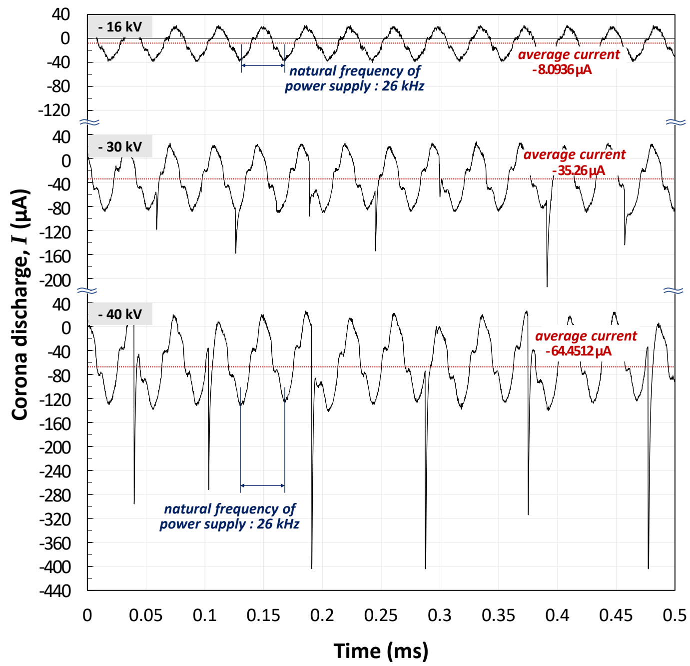

Figure 9: Waveforms of Trichel pulses of the distilled water electrospray (Q = 10 mL/min).

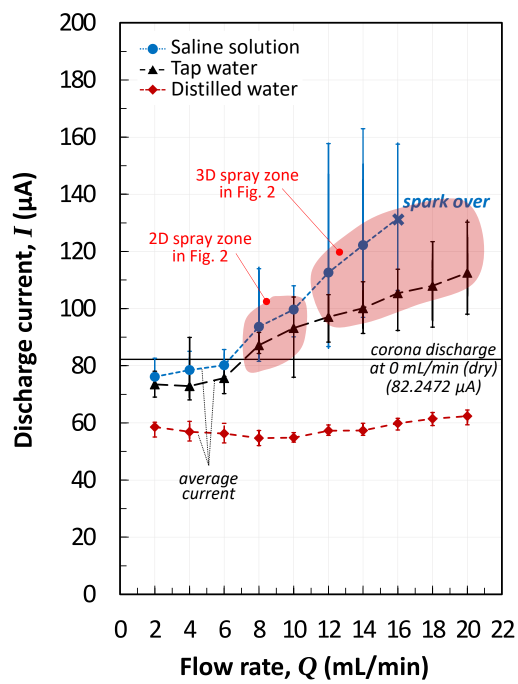

Figure 10: Discharge current according to electrical conductivity and flowrate (V = -34 kV).

Fig. 10 shows the discharge current of electrospray with flowrate increasing. The experiment is conducted at -34 kV using three different electrical conductivity of spray fluid (distilled water, tap water, and saline solution). At flow rates above 6 mL/min, the flow rate and discharge current were proportional. In other words, the contribution of current delivered by the charged droplets is dominant over corona discharge. This implies that it is easier to collect dust particles by electrical attraction as the flow rate increases. For distilled water which has very low conductivity, the current is lower than dry condition (82.2472 μA). It means that the droplets are not in charged state and cannot capture the particles dust inductively (Kim *et al*., 2020). So, it is not suitable as working fluid for dust collection.
The power consumption of single nozzle electrospray system is analyzed based on the electrospray corona current in Fig. 11. In this graph, the higher power consumption means that the droplet can contain more electric charge when the same voltage is applied at liquids. Thus, the droplets can attract more dust particle of submicron, and it can have better performance of dust removal. The power consumption tends to increase with applied voltage and electrical conductivity of aqueous solution. However, when the electrical conductivity is higher than around that of tap water, the rate of increase in power consumption is small compared to the increase in conductivity. Even, as you can see the case of saline solution, it quickly reaches to *spark over* and it is hard to use. The tap water is suitable for application in electrospray scrubber. As a result of the PM removal performance evaluation of cyclone electroscrubber with electrospray based on optimal operating conditions derived from the lab-scale experiments, the removal efficiency of PM10 was 99.65%, PM2.5 was 97.59%, and PM1.0 was 90.95%.

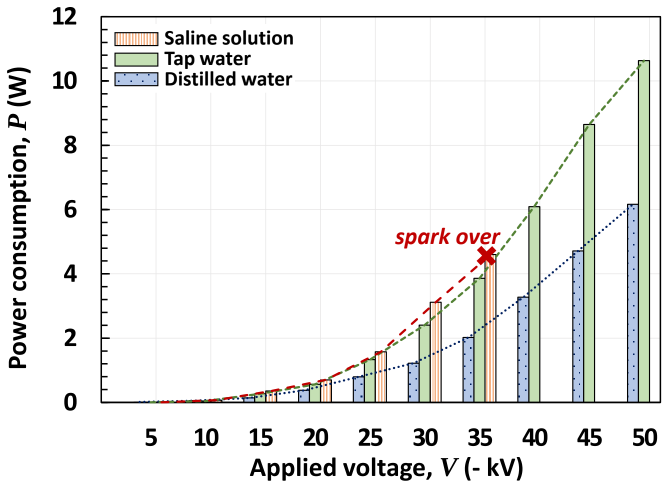

Figure 11: Relationship between power consumption and applied voltage (Q = 10 mL/min).

3. CONCLUSIONS

In this paper, electrospray of aqueous solution is visualized, and discharge characteristics are experimented for designing electrospray scrubber. The electrospray modes are classified through the visualization and the 3D spray is more suitable to dust collect because of wide spray area. During electrospray, liquid droplets carry the electron charge, and it is represented as discharge current. Liquid has higher electrical conductivity, the more the current flows. The Trichel pulse the does not appear except for distilled water which has very low electrical conductivity. Comparing flow rate and current graph, the flow rate and discharge current are proportional at flow rates above 6 mL/min. The more droplet charged means the dust removal efficiency can be higher. Through the comparison of power consumption in tap water and saline solution, there is a limit to amount of charge that can exist on a surface of droplet. As the result, tap water is suit for use not only terms of conductivity but also economic, and accessibility.

NOMENCLATURE

D	nozzle diameter	(mm)
I	discharge current	(μA)
P	power consumption	(W)
Q	flow rate	(mL/min)

V	applied voltage	(kV)

Greek symbol

τ	Trichel pulse period	(μs)

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