Combination of Electrospray with Electrostatic Precipitator for Collection Efficiency Enhancement of Fine Particles

Jong-Ho Kim, Jong-Hyun Kim, Hwa-Su Lee, Hyun-Ha Kim, Atsushi Ogata

***Abstract*—Electrospray was employed upstream of an electrostatic precipitator (ESP) to enhance the collection efficiency of monodisperse nanometer-sized particles. The electrospray of deionized water produced water droplets with a size range from several tens to several hundreds μm. The visible combined effect of the ESP with the electrospray was found for the collection of particles larger than about 200 nm. The combination of the ESP and the electrospray was also found to be effective in reducing the energy consumption of ESP.**

***Index Terms*—Electrostatic Precipitator (ESP), Fine Particle, Electrospray, Collection Efficiency**

I. Introduction

Air pollution problem of particulate emission has been shifted from micrometer- to nanometer-sized particles. As the particle size decreases the potentials of chemical and catalytic effects in human health increase dramatically. In this sense, the control of nanoparticles has a higher priority in terms of human health despite of its less contribution in weight concentration. Environmental standard and emission regulations are also expected to be more stringent in the future. This is common trend in many countries. EURO 5 standard for automobile will include the regulation on the number concentration of nanoparticles.

Electrostatic precipitator (ESP) has been used for the control of particles in many industrial field since the first success of practical use by Cottrell in 1907 [1, 2]. There have been considerable amount of scientific research, and substantial progress has been made both in scientific understanding and practical use. One of the important applications of ESP has long been fly ash control from coal fired power plants. Back corona problems encountered in treating fly ash with high resistively encouraged many investigations and bought out a further progress such as pulse energization, gas conditioning, moving electrode and operation temperature (cold- and hot-side ESP).

Charging process is an important step influencing the collection efficiency of dust. The well-known two important charging processes are field charging and diffusion charging. The field charging is known to be effective for the large particles. On the other hand, diffusion charging becomes dominant as the particle size decreases. The valley area where the two charging mechanism are week is usually found around the particle size of 0.2 μm. Several methods have been proposed and demonstrated to increase the collection efficiency of submicron particles. These methods include precharging, particle agglomeration and combination with other technology such as a bag filter, a cyclone and a scrubber. For the agglomeration of submicron particles into larger ones, AC corona or a dielectric-barrier discharge (DBD) has been implemented in front of ESP [3, 4].

The application electrically charged water droplets for the collection of aerosol particles charged to the opposite polarity has been proposed by Penny in early 1940's [5]. Pilat investigated the use of electrospray in wet scrubber for dioctyl phthalate (DOP) aerosol and reported a collection efficiency increase from 68.8 % to 93.6 % [6]. He also reported pilot scale field test of this system. A very similar system, charged droplet scrubbing, was also reported by Lear *et al* for the removal of fine particles [7]. One of the important parameters in particulate scrubbers is the liquid/gas (Q_L/Q_G) ratio. Typical Q_L/Q_G ratio in the conventional scrubber ranges from 1 L/m^3 to 5 L/m^3 [8]. On the other hand, the electrically assisted wet-scrubber is usually operated with the Q_L/Q_G ratios of about 0.1 L/m^3 ~ 0.01 L/m^3, which is one or two orders of magnitude less than the conventional scrubbing process [7]. An electrospray scrubber using a twin-fluid nozzle, being large in the Q_L/Q_G ratios at 1.8 L/m^3, has also tested for the removal of oppositely charged particles [9]. Recently, Tepper *et al* reported the electrospray-based air purifier using water-ethanol mixture [10].

In this work, we focused on the use of electrospray as a tool to increase the collection efficiency of nanometer sized particles. Electrostatic interactions are effective in this size range. The performance of particle collection was evaluated by number concentration rather than the conventional weight

Jong-Ho Kim is with the Department of Environmental Engineering, HanSeo University, Korea (e-mail: kimjh@hanseo.ac.kr).
Jong-Hyun. Kim is with the Department of Environmental Engineering, HanSeo University, Korea.
Hwa-Su Lee is with the Department of Environmental Engineering, HanSeo University, Korea.
Hyun-Ha Kim is with the National Institute of Advanced Industrial Science and Technology (AIST) Tsukuba, Ibaraki 305-8569 Japan (corresponding author to provide phone: +81-29-861-8061; fax: +81-29-861-8866; e-mail: hyun-ha.kim@ aist.go.jp).
Atsushi Ogata is with the National Institute of Advanced Industrial Science and Technology (AIST) Tsukuba, Ibaraki 305-8569 Japan (e-mail: atsushi-ogata@ aist.go.jp).

concentration (mg/m^3). A major drawback of the weight concentration measurement is long sampling time because of the necessity of collecting sensible particle mass on each particle size. This time averaged sampling also looses important information on the time varying nature (i.e. agglomeration) of the nanoparticles. We also focused on the energy saving in ESP by the combination with electrospray.

II. Experimental

A. Set-up

Figure 1 illustrates the experimental setup used in this study. The electrospray system consisted of three nozzles. The diameter of the nozzle was 0.22 mm. Wires (1 mm diameter) were used as ground electrode for the electrospray. The gap between the nozzle and the wire was 20 mm. Deionized water with electrical conductivity of 3.3 μS/cm was used for the electrospray. Neither a feeding pump nor a pressure control system was applied to the nozzle.

The typical parameters of the ESP are summarized in Table 1. A plate type ESP was installed in the acrylic duct. The electrode gap in the ESP was 25 mm. The size of the collection electrode was 150 mm (L) × 100 mm(H). The corona electrode was made of stainless steel of 1 mm in diameter. An induction draft DC-fan was used to get air flow. A high efficiency particle (HEPA) filter was installed at the inlet of the duct, which enabled us to get aerosol free gas sample. An average gas velocity was 0.8 m/sec, which corresponded to the flow rate of 0.48 M^3/min. The gas velocity was measured using an anemometer (Kanomax Japan INC., Model 6004). A DC power supply capable of delivering up to 20 kV was used. Since most of industrial ESP is operated with negative polarity, the ESP was energized with negative DC high voltage.

Test particles was prepared using 1,1,3,3-tetramethyl disiloxane (TMDS;, Aldrich) as precursor. The bottle with TMDS solution was set in a coolant filled bath maintained at -5 ^{o}C. Pure nitrogen (60 cm^3/min) was fed to the TMDS containing bottle, and then mixed with air (150 cm^3/min) just prior to be injected to the electrical furnace. The vaporized TMDS was converted into solid SiO_2 particles via thermal reaction in the furnace. The temperature in the electrical furnace was found to be important factor determining the size distribution of the particle. We fixed the furnace temperature at 750 ^{o}C based on some preliminary tests. The test particles were introduced to the wind tunnel just after the HEPA filter.

B. Measurement

The particle size and the number concentration were measured using a particle spectrometer (PMS, LAS-X II) covering a size range from 90 nm to 7.5 μm. Particles measurement was repeated at 10 sec interval and the 10 measurements were averaged at each condition. A particle diluter (Matter Engineering, Model MD19-1i) was used prior to the particle spectrometer to keep the number concentration within the measurement range. Dilution ratio was set at 147:1.

TABLE 1
Basic parameters of ESP

Parameter	Typical values	This study
Gas velocity	2-6 m/sec	0.8 m/sec
Temperature	100-250 ^{o}C	RT
Spacing	250-500 mm	25 mm
Electric field	~ 7 kV/cm	~ 7.6 kV/cm
Polarity	negative	negative
Specific corona power	0.1~0.5 Wh/m^3	0.06~0.42 Wh/m^3
Specific collection area	20 ~ 100 sec/m	0.13 sec/m

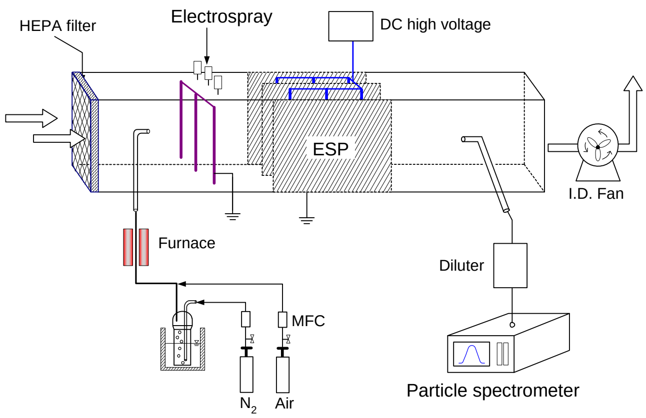


Figure 1. Experimental setup

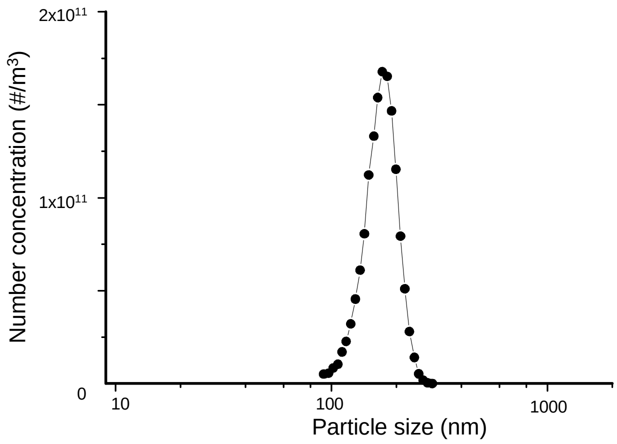


Figure 2. Typical size distribution of test particles.

Figure 2 shows a typical size distribution of the test particles. The produced particle exhibited a monodisperse size distribution. The mean diameter and average number concentration were 220 nm (standard deviation = 0.19) and 2.3 $\times 10^{12}$ particle/m^3, respectively.

Digital oscilloscope (Tektronix, Model TDS 3034B) was use to measure the applied voltage. High voltage probes (Tektronix, Model 6101A) were used to monitor the applied voltages of the ESP and the spray nozzles. A register of 1 kΩ was inserted to the ground line in series to measure the discharge current in the ESP. A high speed digital camera (Photron Co.; FASTCAM-SA1.1 Model 675K-M2) was used to observe the detailed with resolved images of the electrospray.

III. RESULTS AND DISCUSION

A. Voltage-Current (V-I) characteristic

Figure 3 shows the V-I characteristics of (a) the electrospray and (b) the ESP. The current in the electrospray increased with the rise of applied voltage and reached to 10 μA at 10 kV. Considering the normal current values in electrospray are in the range of several tens nA [11, 12], the sharp increase of current at above 5 kV can be attributed to the corona discharge. In the case of ESP, corona started at 16.2 kV. The discharge current sharply increased as the applied voltage exceeded the corona onset voltage. It reached to about 600 μA at the applied voltage of 20 kV. The measured current data matched well with the exponential growth fitting curves. The large difference in the corona onset voltage between the electrospray and the ESP due probably to the different curvature of the corona electrode (nozzle tip *vs* wire) and the gap distance. From the V-I curves, one can see that the energy consumption in the electrospray can be neglected compared to that in the ESP. The spray mode in the voltage range was dripping mode. The size range of the water droplets was from 0.3-2 mm.

Figure 4 shows high speed camera images of the electrospray at different applied voltage. The droplet size decreased with the increase of applied voltage to the spray nozzle. The ratio of smaller droplets was increased with voltage. Water droplets were ejected from the spray nozzle in a dripping mode within the tested voltage range. The droplet size, estimated from the images, exhibited two different size ranges; one in several 10s range and the other in several 100s micrometers.

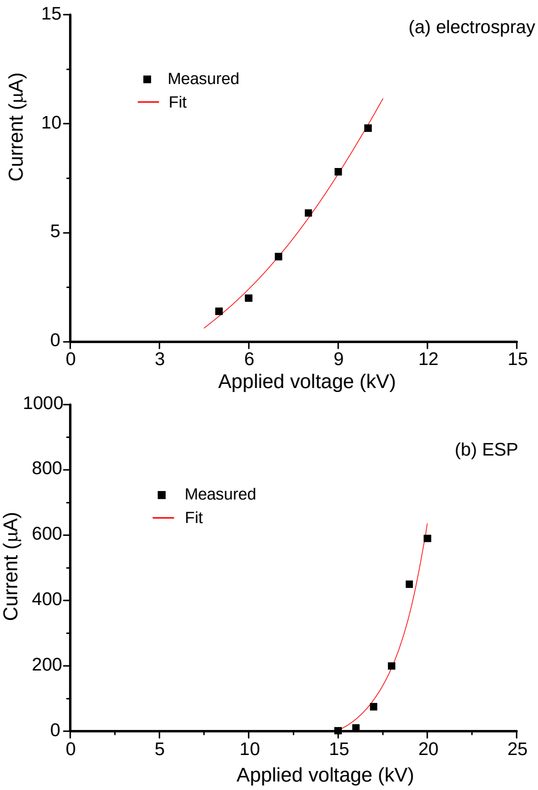


Figure 3. Voltage-current characteristics in (a) electrospray and (b) ESP. Negative polarity was used in both cases.

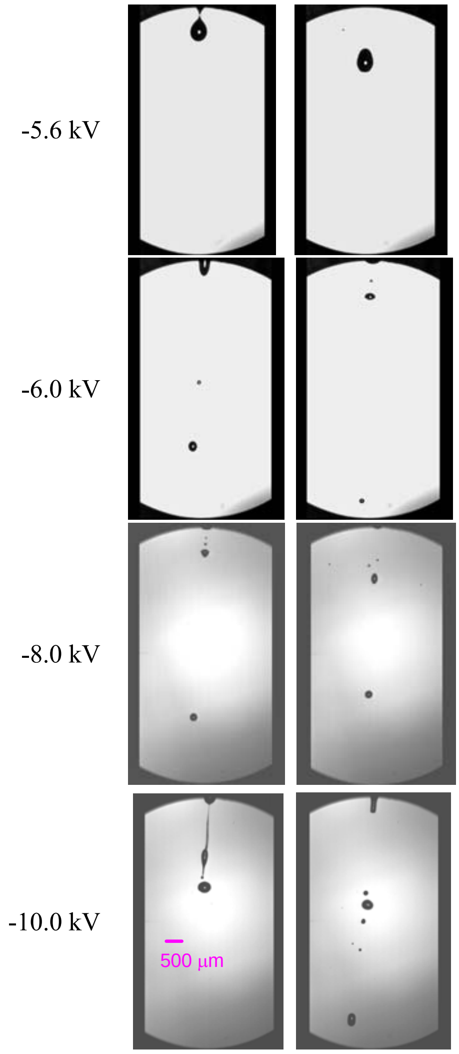
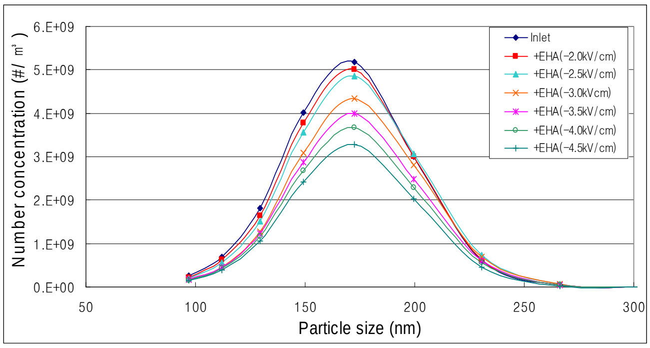


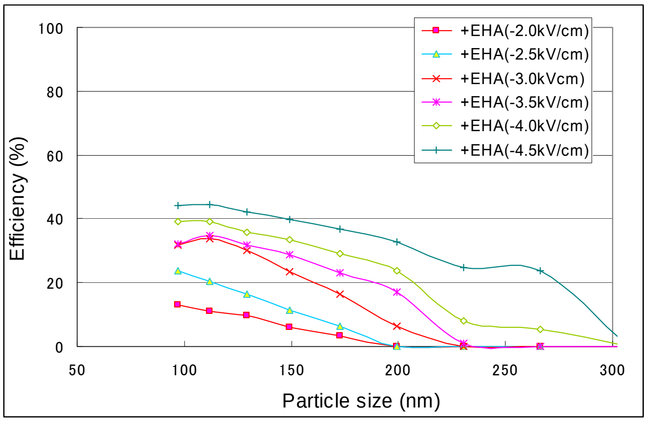
Figure 4. Photos of electrospray at different applied voltage. (10000 fps at 1 μs gate time).

B. Particle Collection by Electrospray

Prior to the integration of the electrospray and the ESP, particle collection efficiency of each process has been tested. Figure 5 summarize the effect of electrospray on the particle collection. The amount of water spray was 0.34 mL/min, which corresponds to the Q_L/Q_G ratio of 0.0007 L/m^3. It is still quite low compared to the Q_L/Q_G ratio of about 0.05 ~ 0.2 L/m^3 with the electrospray for particle removal [7]. For given particle size, the removal efficiencies increased with the voltage applied to the electrospray. The liquid amount ejected form the nozzle is basically dependent on the applied voltage. The electric field formed at nozzle tip produce electrostatic pressure, which plays an important in the electrospray [13]. The increase in applied voltage makes electrostatic force strong, resulting in the increase of liquid flow rate. This was supported the high speed camera images of the electrospray (Fig.4). On the other hand, the partial collection efficiency decreased with the increase of particle size. Considering the size range of the tested particles, it is expected that the contribution of inertial impaction and interception will be negligible. It is known that the Brownian

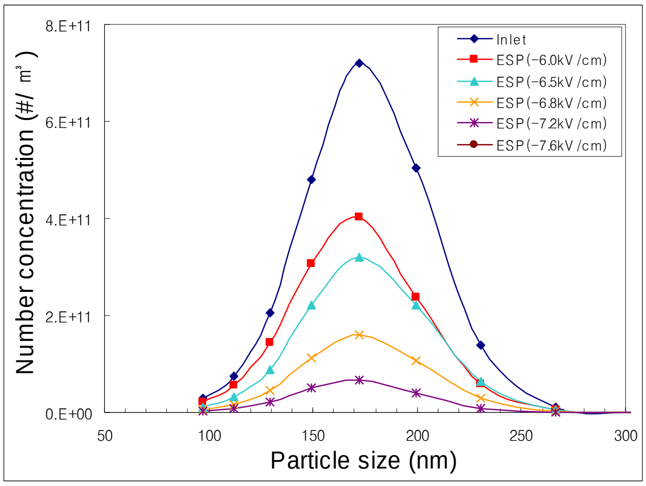


(a) Size distribution

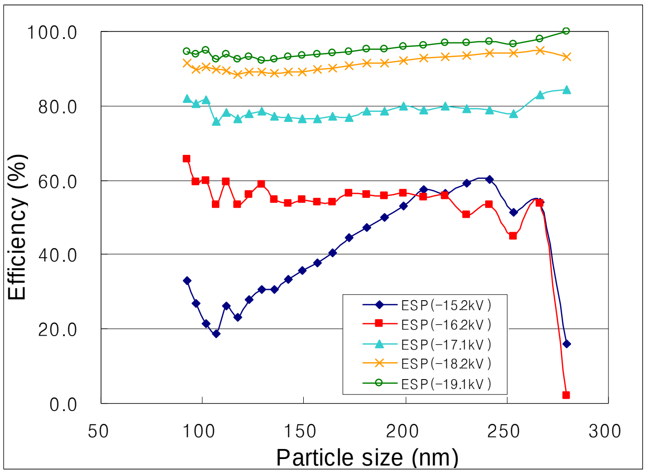


(b) Collection efficiency

Figure 5. Particle removal by the electrospray only.



(a) Number concentration



(b) Collection efficiency

Figure 6. Particle collection by the ESP only.

diffusion of submicron particles plays an important role in the particle collection using a wet scrubber. The electrostatic forces may increase on the relative velocity between the water droplet and particles. The velocity of the water droplets with several tens μm range was about 20 m/sec, which is about 20 times higher than the gas flow velocity in the ESP. Furthermore, agglomeration of submicron particles become efficient when the nuclei (water droplets in this case) is large enough compared to the size of particles [4]. The water droplets ejected from the electrospray were in the range from 20 μm to 500 μm, which is large enough compared to the test particles.

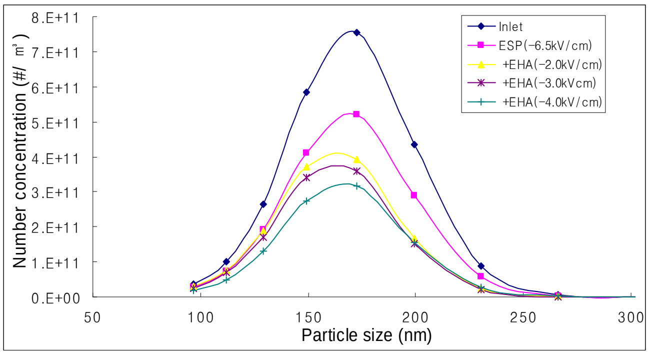
C. Particle Collection by the ESP

Figure 6 shows the performance of the ESP at different applied voltages. Applied voltage was found to be a primary parameter determining the particle collection efficiency in the ESP. The trend in the particle collection efficiencies for each particle size was clearly different from that of the electrospray. At near the corona onset voltage of -15kV (-6.0 kV/cm) partial collection efficiency increased with the particle size and reached maximum at 230 nm, and then sharply decreased for the larger particles. This sharp decrease in the collection efficiency was also observed at 16.2 kV. One possible reason for these decreases is the agglomeration of smaller particles into larger ones. When the applied voltage become higher than the 16.2 kV, where the corona current exhibits an exponential growth, these sudden drops in collection efficiency disappeared. It does not mean that the agglomeration process completely disappear at normal operation voltage in ESP. The balance between the agglomeration and the particle collection may shift to one end according to the electric field. The agglomeration process can be induced by both the charged and uncharged water droplets and by the ions as well (i.e. ion-induced nucleation). Although being small the degree, collection efficiencies increased with particle size at the applied voltage higher than 16.2 kV (-6.5kV/cm).

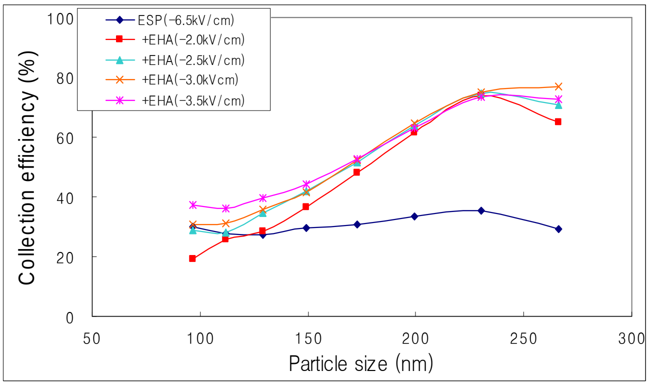
D. Particle Collection by the Combination of Electrospray and ESP

Figure 7 shows the combined effect of the electrospray and the ESP for the removal of fine particle. The applied voltage in the ESP was fixed at -16.2 kV (- 6.5 kV/cm), whereas the electrospray was operated with varying the applied voltage. The particle collection efficiency increased with the particle size. The slopes of collection efficiencies are the largest with the combined process. On the other hand, the collection efficiencies for the particle size smaller than 200 nm were lower than those with the ESP alone. And the degrees of enhancement by the electrospray were found to be less prominent than the electrospray alone. This result indicated that the working mechanism of particle collection in the combined process differs from the separated process. The detailed mechanism of particle collection in the combined process is unclear at this stage, and need further investigations.

Beside the synergistic effect in collection efficiency, energy consumption is also important issue in the combined process. As was indicated by the V-I characteristic, energy consumption in the electrospray was quite small compared to the ESP. Nevertheless, integration of the electrospray brought out an evident increase of the particle collection. For example, the partial collection efficiency of the 230 nm was 35.4 % with the ESP alone. It increased up to 75% by combining the electrospray and the ESP.



(a) Number concentration



(b) collection efficiency

Figure 7. Particle collection efficiency with the electrospray.

IV. Conclusion

An electrospray has been used in electrostatic precipitator to enhance the collection efficiency of nanometer sized particles. The major findings of this work can be summarized as follows.

1) Despite the small liquid/gas ratio, a visible influence of the electrospray on the particle collection was observed. The particle collection with the electrospray increased as the particle size decreases. On the other hand, collection efficiencies in the ESP increased with the particle size at applied voltage higher than about 17 kV (-6.8 kV/cm), but their degree was very small.
2) The electrospray of the deionized water produced micrometer sized droplets in a dripping mode. The combined effect became more clear as the particle size increased.
3) The possibility of reduction in energy consumption has also demonstrated by the combined system. Further enhancement may possible by optimizing the operational parameters such as liquid/gas ratio, spray mode, polarity and the proper configuration.

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