This article was downloaded by: [National Taiwan University]

On: 14 April 2009

Access details: Access Details: [subscription number 908165577]

Publisher Taylor & Francis

Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK

Aerosol Science and Technology

Publication details, including instructions for authors and subscription information:

<http://www.informaworld.com/smpp/title-content=t713656376>

Loading Characteristics of a Miniature Wire-Plate Electrostatic Precipitator

Sheng-Hsiu Huang^a; Chih-Chieh Chen^a

^a Institute of Occupational Medicine and Industrial Hygiene, College of Public Health, National Taiwan University, Taipei, Taiwan.

First Published on: 01 February 2003

To cite this Article Huang, Sheng-Hsiu and Chen, Chih-Chieh(2003)'Loading Characteristics of a Miniature Wire-Plate Electrostatic Precipitator',Aerosol Science and Technology,37:2,109 — 121

To link to this Article: DOI: 10.1080/027868203000950

URL: <http://dx.doi.org/10.1080/027868203000950>

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: <http://www.informaworld.com/terms-and-conditions-of-access.pdf>

This article may be used for research, teaching and private study purposes. Any substantial or systematic reproduction, re-distribution, re-selling, loan or sub-licensing, systematic supply or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

Loading Characteristics of a Miniature Wire-Plate Electrostatic Precipitator

Sheng-Hsiu Huang and Chih-Chieh Chen

*Institute of Occupational Medicine and Industrial Hygiene, College of Public Health,
National Taiwan University, Taipei, Taiwan*

In this work, in order to investigate the particle loading effects on the performance of an electrostatic precipitator (ESP), simultaneous measurements of the dust cake thickness accumulated on the collection plates, ESP's collection efficiency, corona discharge characteristics, and ozone concentration were conducted experimentally. A laboratory scale single stage wire-plate ESP was used for the aerosol loading test. Two kinds of particulate matter, cement and aluminum oxide (Al_2O_3), were generated by using a Palas Powder Disperser. A displacement meter was used to monitor the dust cake thickness accumulated on the collection plates. A scanning mobility particle sizer was used to measure the particle size distribution and number concentration upstream and downstream of the ESP. Ozone generated by the ESP was sampled 20 cm downstream of the ESP exit and measured with an ozone analyzer. The Dioctyl Phthalate (DOP) was also used as a liquid challenge agent in order to investigate the loading effects of liquid particles on the ESP performance.

The results showed that when challenged with cement particles, the ion current decreased with increasing dust cake thickness under a constant electrical field strength. Moreover, the collection efficiency and ozone generated by corona discharge decreased as the loading test progressed. For example, when the dust layer was about 5 mm in thickness, the output current and the ozone concentration decreased about 33 and 44%, respectively, and the collection efficiency (300 nm particle) decreased about 4% at a fixed electrical field strength of -4.2 kV/cm. However, the ion current increased as aluminum oxide particles deposited on the collection plates. The increase in ozone concentration and aerosol penetration was mainly due to the occurrence of back corona, evidenced by the existence of the caves on the surface of the dust layers. In the case of testing with cement particles, the ion current rises after about 20 min of loading test and then decreases with time, while ozone concentration increases synchronously.

INTRODUCTION

The electrostatic precipitation process involves several complicated and interrelated physical mechanisms. The particles are given electric charges by forcing them to pass through a positive or negative corona, a region in which gaseous ions flow. Charged particles are then deflected from the main gas stream by an electric field to precipitate onto the collection plates, where they form dust layers of growing thickness. In theory, particles should be repelled from the corona discharging wires because of the strong ionic wind flow. Yet, one often observes particles, the finer ones in particular, depositing on the wires. This may appear a contradiction of the theoretical considerations. The reason is that fine particles are greatly influenced by turbulence and may therefore be blown onto the discharge electrodes. Also, particles may receive positive charges if within a very strong electric field closely surrounding it (Dorman 1974).

The corona discharge characteristic of an electrostatic precipitator (ESP), which is a very important factor for particle collection efficiency, depends on several parameters: wire-to-plate spacing, wire diameter, wire material, applied voltage and its polarity, etc. Significant efforts both in theoretical and experimental studies have been made for the improvement of corona discharge. There have been a number of significant advances resulting in ESPs with very high collection efficiencies (Awad and Castle 1975). However, in practical use of an ESP, the discharge electrodes and collection plates become contaminated with an increasing operational time. The properties and behavior of the dust layer interest us because they affect the external conditions in which the separating process takes place. From this perspective, any dust layer is a nuisance, which tends to impair the collection efficiency. However, only a relatively small number of studies have addressed the effects of particle accumulation on the discharging electrodes or the collection plates. Although a theoretical approach for describing the electrical characteristics of a precipitated dust layer in an ESP was proposed (McDonald et al. 1980), quality experimental data, which are necessary for constructing appropriate models and for use in comparing the predictions of models, are incomplete or unavailable.

Received 12 July 2000; accepted 14 May 2002.

The authors would like to thank the National Science Council of Taiwan for financially supporting this research under contract no. NSC 90-2320-B-002-039.

Address correspondence to Dr. Chih-Chieh Chen, Institute of Occupation Medicine and Industrial Hygiene, College of Public Health, National Taiwan University, Taipei, Taiwan, People's Republic of China. E-mail: ccchen@cems.ntu.edu.tw

Generally, the collection efficiency of an ESP decreases as the discharging electrodes and collection plates are contaminated with particles. Therefore both the discharging electrodes and collection plates have to be cleaned periodically. This is usually accomplished by knocking them loose from the wires and plates, allowing the dust layer to slide down into a hopper from which they are evacuated. In many practical applications, removal of the collected particulate layer from the collection plates presents a serious problem since the removal procedures introduce collected material back into the gas stream, causing a reduction in collection efficiency. Particle resistivity is one of the major factors that govern the behavior of deposit layers and thereby its effect on the separating process. In general, the most optimal domain of resistivity for the ESP is in the range from 10^4 to 10^{11} Ω -cm (Ogawa 1982). In practice, the range of particle resistivity is always divided into 3 broad categories: low-resistivity, normal-resistivity, and high-resistivity (Dorman 1974; Bohm 1982). Although the effects of particle resistivity on the precipitation process are well known, experimental data is seldom available.

In using an ESP as an indoor air cleaner, ozone generation due to corona discharge is an important problem. As aforementioned, the corona discharge characteristics might be altered because of the contamination of the discharging wires and/or collection plates. Therefore it is conceivable that the ozone generation rate may differ after the electronic air cleaner has been used for a period of time.

Several studies showed the influence of the discharge electrode surface contamination on the ozone generation (Dorsey and Davidson 1994; Kanazawa et al. 1997). The contaminated electrode was suggested as a cause of ozone generations. The most plausible mechanism for electrode contamination to increase the ozone generation rate is through an increase in ion

current (Dorsey and Davidson 1994). However, even though the experimental data are considered to be practical and useful, the experimental conditions were not identified clearly. Meanwhile, the corona discharge characteristics may be altered due to the contamination of collection plates. In a recent review of air cleaner test methods currently adopted, Davidson and McKinney (1998) showed that neither test based on clean air delivery rate (AHAM 1989) and ASHRAE 52.1 (1992) accounted for changes in performance that occur with use. Although periodic cleaning, which is often recommended by manufacturers may avoid the degradation of air cleaner performance, very little reliable quantitative data is published that relates the ozone generation rate and collection efficiency to contaminated wires and/or collection plates.

In this study, a laboratory scale wire-plate ESP was designed, built, and operated in a test chamber. The influence of particles with different electrical property accumulation on both the discharging electrodes and the collection plates were experimentally studied. Simultaneous measurements of the dust cake thickness accumulated on the collection plates, ESP's collection efficiency, corona discharge characteristics, and ozone concentration were conducted in order to investigate the particle loading effects.

EXPERIMENTAL MATERIALS AND METHODS

The experimental setup consisted of 6 components: a clean air test chamber, a particle generation system, a pilot scale one stage wire plate ESP, a particle size distribution and number concentration measurement system, a dust layer thickness detection device, and an ozone analyzer. The schematic diagram of the test system is shown in Figure 1 and experimental conditions are listed in Table 1. The test chamber was made of Plexiglas and operated at the ambient temperature. The air

Figure 1. Schematic diagram of the experimental setup.

Table 1
Experimental conditions

Dimensions and operating conditions	ESP performance	Loading test
Radius of wire, mm	0.3, 0.4, 0.5, 0.8	0.3
Number of wires	3	3
Length of ESP, mm	300	300
Width of ESP, mm	120	120
Height of ESP, mm	76	76
Wire to wire space, mm	42	42
Applied voltage of corona wire, kV(negative)	15~38	25
Air velocity, cm/s	9.1 and 18.3	18.3
Air temperature, °K	297	297
Relative humidity, %	5~10	5~10

velocity used in the study, if not specified, was 18.3 cm/s (equal to a total flow rate of 100 L/min). The relative humidity of the gas was about 5–10%. Two kinds of solid challenge particles, cement and aluminum oxide (Al_2O_3), were dispersed using a Palas Powder Disperser (model BEG-1000, Germany). The Palas Powder Disperser utilizes a variable-speed turntable to transport dust at a constant rate to the test chamber. Dioctyl Phthalate (DOP), which is a liquid material, was also used as challenge aerosol in order to investigate the loading effects of liquid particles on the ESP performance. DOP particles were generated by using a modified 4 jets atomizer. In order to avoid the particle charge effect, the particles were then passed through a 22.5 mCi Po-210 radioactive source (model P-2001, NRD Inc.) to neutralize the aerosol particles to the Boltzmann charge equilibrium. A laboratory-scale 3 wires single-stage wire-plate ESP (with dimensions of 12 (W) $\times$ 30 (L) $\times$ 7.6 (H) cm) was designed, built, and installed in the test section as shown in Figure 1. Copper wires that are 0.3 mm in diameter were used as discharge electrodes. The ESP was energized by a high voltage DC power supplier (model SL50PN300, SPELLMAN High Voltage Electronics Corporation) to generate a negative corona. Values of the output voltage and current were read directly from the power supply. A scanning mobility particle sizer (SMPS, model 3934U, TSI Inc.) and an ultrafine condensation particle counter (UCPC, model 3025A, TSI Inc.) were used to measure the particle size distribution and number concentration, respectively. The measuring point was positioned at the center of the cross-sectional area of the test chamber. The aerosol flow was sampled through a sampling tube that was placed 20 cm downstream of the ESP outlet. Particle number concentration data obtained in the power-on and power-off modes were used to evaluate the aerosol penetration through the ESP. A displacement meter (LK-081, Keyence Corp. Osaka, Japan) was used to monitor the dust cake thickness accumulated on the collection plates. The displacement meter measures using triangulation. A laser diode shines a beam of light to the target. The light will diffuse off the surface and back

to the sensor. The light is focused onto a charge coupled device (CCD) detector. As the target moves away from the sensor, the focused spot will move toward one end of the CCD. As the target moves toward the sensor, the focused spot will move toward the other end of the CCD. The position of the laser spot on the CCD is directly proportional to the distance to the target. The ozone generated by the ESP was sampled 20 cm downstream of the ESP exit and measured with an ozone analyzer (model 400, API Inc., San Diego, CA).

Data were acquired on a personal computer equipped with a 12-bit A/D board. Ozone concentration, ion current, particle number concentration, and dust layer thickness were recorded as 1 s averages. Current-voltage (I-V) curves were acquired for each test. All airflows were controlled and monitored by mass flow controllers (Hastings Instruments, Hampton, VA).

The electrical resistance depends on many variables, including composition, size, compaction, electric field applied to the layer, and the temperature, humidity, and chemical composition of the surrounding air (White 1974). Although using the resistivity value of bulk material measured under specified conditions as a reference might be a simple way, the most logical approach is to measure it under the real conditions. The severity of back corona increases with the resistivity of the particles (White 1974). Back corona is not significant when resistivity is below 10^{10} Ω -cm. Little or no back corona occurs for resistivities between 10^{10} and 10^{11} Ω -cm. Above 10^{11} Ω -cm back corona begins and becomes increasingly severe as resistivity rises. Table 2 shows the characteristics of challenge aerosols used for loading tests. Two solid particles, cement and Al_2O_3 , were chosen because of their varying resistivities. The commercial availability and the cost were another consideration. DOP was used as a challenge aerosol in order to investigate the loading effects of liquid particles.

The electrical resistivity normally is measured by using the resistivity meter based on the standard ASME PTC-28 code. Due to the lack of an appropriate resistivity meter, a technique (White 1974), which is based on corona current suppression by

Table 2
Characteristics of the challenge aerosols used for the loading test

	CMD* μm		Number concentration number/cm ³	Resistivity Ω -cm
Cement	1.3	1.7	9.77×10^5	8×10^7 (White 1974) 2.7×10^{10} (calculated)
Al_2O_3	2.8	2.2	4.20×10^4	$> 10 \times 10^{14}$ (Shackelford et al. 1994) 10^{12} (Zhuang et al. 2000)
DOP	0.28	1.8	1.19×10^6	—

*Count median diameter.

**Geometric standard deviation.

Figure 2. Experimental results on the I-V characteristic curves of the ESP.

the resistive dust layer, was used in the present study to calculate the dust layer resistivity of cement as follows:

$$\rho = \frac{A}{l} \times \frac{\Delta V}{i}, \quad [1]$$

where ρ is the resistivity of the dust layer, A is the area of the collecting plate, l is the dust layer thickness, ΔV is the Ohm's law voltage drop through the dust layer, and i is the corona current. Moreover, the calculated value of cement's electrical resistivity is shown in Table 2. Notice that this method cannot

be applied to aluminum oxide because of the back corona, as will be discussed below.

RESULTS AND DISCUSSION

ESP Performance

In order to understand the basic properties of the ESP, several tests were conducted before the loading test. The simplest electrical characteristic of an ESP is the current-voltage (I-V) curve. Figure 2 shows the summarized I-V characteristics for various

Figure 3. Ozone generation versus ion current for negative polarity of the corona.

Figure 4. Comparison of aerosol penetration through the 0.8 mm wire and 0.3 mm wire ESP versus particle size for a given corona current.

wire diameters under the particle-free condition. The temperature and relative humidity in the test chamber were 24°C and 5%, respectively. The air velocity was 9.1 cm/s. As expected, electrical characteristics were affected by wire diameter. With decreasing wire diameter, corona onset voltage decreased and the I-V curve shifted to a higher current for a given voltage. These results agreed well with data presented by Boelter and Davidson (1997).

Just as is shown in Figure 3, for a fixed wire diameter ozone generation was linearly proportional to the current. At a fixed ion current, the ozone concentration decreased with decreasing elec-

trode wire diameter. For example, the ozone concentration decreased from 6,200 ppb to 2,500 ppb as wire diameter decreased from 0.8 mm to 0.3 mm at a flow rate of 50 L/min. This trend also agreed with a previous study (Boelter and Davidson 1997).

We also examined the aerosol penetration through 0.3 and 0.8 mm wire ESP of different air velocity and electrical field strength although the figures are not shown in this paper. In general, the aerosol penetration increased with increasing air velocity because a lower air velocity allowed a longer retention time for particles to deposit on the collection plates. When tested

Figure 5. Comparison of power consumption of ESP to different wire size versus aerosol penetration for a given particle size.

Figure 6. The particle loading effects of cement dust on the ESP performance: (a) dust cake thickness, mm (b) current, mA, (c) aerosol concentration, #/cm³, and (d) ozone concentration, ppb, all are shown as a function of loading time.

at the same air velocity (18.3 cm/s), aerosol penetration through the ESP clearly decreased when the electrical field strength increased.

At the same discharged current level, the aerosol penetration through the ESP with a larger discharging wire (0.8 mm) was lower than that with a smaller one (0.3 mm), as shown in Figure 4. This is because for a larger wire, the applied voltage should be higher in order to achieve the same level of ion current (as shown in Figure 2) in the ESP with a smaller discharging wire. Therefore the effective migration rate of particles in the ESP with a larger discharging wire is larger, although the particle charges are the same. The difference of aerosol penetration through the ESP with different wire diameters became unobvious as the ion current increased. The relationship of power consumption, which is defined as the product of applied voltage and ion current, and aerosol penetration of particles that have the minimum collection efficiency (245 nm) is shown in Figure 5. As the power consumption increased, both the electrical field strength and the ion density in the ESP increased and caused more particles with larger electrical migration velocity to deposit on the collection plates. Therefore aerosol penetration decreased with increasing power consumption. Moreover, to achieve the same level of collection efficiency, it is more energy conservative to use smaller discharging wire. Therefore in the following loading test, 0.3 mm wire was chosen as the discharge electrode.

Loading Test

The ESP performance deteriorated due to particle contamination of both the collection plates and the discharging electrodes. Figures 6a–d show the cement particle loading effects on the ESP performance. Figure 6a shows the dust layer thickness of cement particles as a function of precipitation time. The dust layer increased with increasing precipitation time and was about 5 mm

thick at the end of loading test (about 120 min). During the period of 90–100 min, the view window on the top of the ESP was contaminated. Therefore the displacement meter did not work properly and resulted in data points missing during this period. Unfortunately, because of the limitation of the experimental apparatus used in this work, the uniformity of the dust layer was not measured. However, according to the visual observation, the dust layer is thick at the electrode region and becomes thinner along the direction of the airflow. There are many factors, including the kind of particles (Bohm 1982), the size and distribution of the particles (Bohm 1982; Bush 1984), the ion current and the electrical field strength (Yamamoto et al. 1998), and the shapes and mutual arrangement of the particles (Bohm 1982), may affect the structure of the dust layer. It is worth further study to investigate the effect of these factors on the morphology of the dust layer, and then to clarify the relationship between dust layer structure and the rapping reentrainment. Figure 6b shows the ion current characteristic of the ESP as a function of precipitation time. Subjectively, the curve in Figure 6b can be divided into 4 stages: clean electrodes stage, loading start stage, tuft discharge stage, and stable decreasing stage.

At the beginning of the test, the gas stream in the test chamber was free of particles and both the wire and collection plates were clean and polished. Therefore the corona began at a glow discharge (McLean 1988), which spread quickly over the whole surface of the wire. At a electrical field strength of -5 kV/cm, the ion current was about 0.16 mA and did not change before the Palas dust feeder was turned on, as shown in Figure 6b. As the Palas dust feeder was turned on, the ion current decreased to about 0.13 mA as a result of the masking effects of cement particles on the ionic flow. After 20 min of the loading test, the ion current increased dramatically and was not stable, as is shown in the third stage of the current-precipitation time curve. The fluctuation may be due to the fact that the wire became contaminated

Figure 7. The cement aerosol penetration through the ESP at the beginning and the end of the loading test.

Figure 8. The aluminum oxide particle loading effects on the ESP performance.

and the glow degenerated first to a series of unstable discharges, then to discrete tuft discharges uniformly distributed along the wire's length but pointing in different directions around its surface. Once the tuft corona emerged, one of the main effects was that for a given applied voltage the ion current increased (McLean 1988). The phenomenon did not result from the back corona effect because (1) the calculated resistivity of the cement dust layer is $2.7 \times 10^{10} \Omega\text{-cm}$, which is in the range of little or no back corona occurs (White 1974); (2) there was no back corona cave observed on the dust layers. Finally, as the cement particles gradually built up on the wire, the ion current was reduced because of the voltage drop across the dust layer and also the increase in the radius of the wire.

The total particle number concentration measured by the SMPS system that penetrated through the ESP as the test progressed is shown in Figure 6c. The aerosol penetration increased with increasing test time due to the reduction of the effective migration velocity of the particles. Figure 6d shows the ozone concentration downstream of the ESP. As expected, the amount of ozone that was generated by the corona discharge was related to the level of the ion current. However, in the third stage, although the ozone concentration also showed a dramatic increase, the level was still lower than that of the first stage. It is speculated that this phenomenon may have very likely resulted from the lower ion energy caused by the dust layer accumulated on the wire, and probably in part due to the reaction of ozone and cement particles.

Figure 7 shows the discrepancy of aerosol penetration of particles in the size range of 30 to 600 nm at the beginning and the end of the loading test. For 300 nm particles, the aerosol penetration through the ESP increased about 4% (from 3.5 to 7.5%) after 120 min of the loading test.

Another solid dust used in the loading test was aluminum oxide, Al_2O_3 . It was chosen because its electric resistivity is larger than $10^{15} \Omega\text{-cm}$ at 25°C (Shackelford et al. 1994). The loading effects of Al_2O_3 particles on the performance of the ESP are shown in Figures 8a–d. The dust layer thickness increased with an increasing precipitation time up to about 5 mm and then decreased dramatically to almost zero due to breakaway by gravity and air drag force. In this case, the ion current increased rapidly at the beginning and then reached a stable stage, as shown in Figure 8b. The back corona emerged as the loading test began (Figure 8b). However, the particle number concentration that penetrated through the ESP did not change much during the test (Figure 8c). The same pattern as shown in Figure 8b was observed for the discrepancy of the ozone concentration (Figure 8d). The fluctuation of ozone concentration shown in Figure 8d is likely due to the occurrence of back corona, not due to the instability of the aerosol generation system. Notice that the particle number concentration shown in Figure 6c was measured by using a SMPS system. The down-scan time was 30 s and the up-scan time was 300 s. Therefore one data point was recorded every 330 s. However, in Figure 8c, the particle number concentration was measured by using a CPC3320. Data were recorded at 1 s averages. That is why the data points were different between Figures 6c and 8c.

Figure 9 shows the I-V curves at the beginning and the end of the loading test. For a given voltage, the ion current decreased when loading with cement particles. On the contrary, the ion current increased when Al_2O_3 particles accumulated on the electrodes and collection plates. The difference apparently depended on the occurrence of back corona. The data points of I-V curves were recorded as 1 min averages. Therefore a near-vertical increasing of ion current and the accompanying lower

Figure 9. Experimental results on the I-V characteristic curves of the ESP before and after loading with cement and Al_2O_3 particles.

Figure 10. The DOP particle loading effects on the ESP performance.

spark-over voltage were averaged out and one not shown in Figure 9.

A different deposition pattern arises when the challenge particle is liquid. These particles depositing on the electrodes are runny enough for them to flow freely down the electrodes. Consequently, only a thin film, which causes a voltage drop, forms

on the electrode. Figures 10a–d show the DOP particle loading effects on the ESP performances. Only a very thin film formed on the collection plates after 215 min of the loading test with challenge aerosols of 60 mg/m^3 , CMD of 275 nm, and GSD of 1.8, as shown in Figure 10a. The displacement meter is very sensitive to vibration, which causes some of the data points

(A)

This trench was scraped on purpose to show the cake thickness.

(B)

The caves formed by back corona

Figure 11. Photographs of dust layers: (a) cement particles and (b) Al_2O_3 particles.

below zero (negative thickness). After 20 min of the loading test, the ion current increased, although the dust layer thickness did not increase significantly (Figure 10b), as did the ozone concentration (Figure 10d). Back coronas are ruled out from the causes by the compact, nonporous nature of the film. The increasing of ion current in this stage might be caused by a changing corona pattern from glow discharge to tuft discharge, because nonuniform deposition of particles on the discharging wires was observed by microscope.

The structure of the dust layer depended largely on the properties of the particles. Figure 11 shows the dust layer of cement and Al_2O_3 particles that formed on the collection plates. The dust layer of Al_2O_3 particles appeared porous and fluffy, whereas it is more compact in the case of cement particles. Apparently, further investigations are needed to study the relationship between dust layer structure and particle reentrainment.

CONCLUSIONS

In this work, a laboratory scale wire-plate ESP was designed, built, and tested in a test chamber. At first, the basic performance properties of the ESP were tested in order to decide the operating conditions used for loading tests. Next, the influence of particles with different electric resistivity accumulation on both the discharging electrodes and the collection plates was experimentally studied. Simultaneous measurements of the dust cake thickness accumulated on the collection plates, ESP's collection efficiency, corona discharge characteristics, and ozone concentration were conducted in order to investigate the particle loading effects.

As a result of the present experimental study, the following conclusions were reached:

1. Experimental results indicated that aerosol penetration through the ESP tested decreased with increasing corona voltage or with decreasing flow rate through the ESP. The penetration was highly dependent on the particle size. The most penetrating particle size of the ESP ranged from 0.2 to 0.3 μm . To achieve the same level of collection efficiency, it is more energy conservative to use smaller discharging wire. Meanwhile, smaller discharging wire produced less ozone.
2. Particle loading effects on the performance of an ESP depend on the properties of the particles. One of the main factors is the electric resistivity. In general, the collection efficiency, ozone concentration, and ion current decreased with increasing dust layer thickness at a constant applied voltage in cement particles. However, at the early stage of the loading test, particles deposited on the discharging wire may change the discharging pattern from glow corona to tuft corona. At this stage, the ion current will increase abruptly and then decrease as the loading test progresses. The results also showed that the ozone concentration would be a more sensitive indicator than the aerosol collection efficiency in response to the change of the ion current.
3. The ion current increased as aluminum oxide particles deposited on the collection plates. The increase in aerosol penetration and ozone concentration was mainly due to the occurrence of back corona, which can be proved by the existence of the caves on the surface of the dust layers.
4. The dust layer of Al_2O_3 particles appears porous and fluffy. It is more compact in the case of cement particles. Further investigations are needed to study the relationship between dust layer structure and aerosol reentrainment.
5. The problem of rapping reentrainment has been studied by many researchers (Bush 1984; Kim and Lee 1998; Lee et al. 1998; Perevodchikov et al. 1998; Yamamoto et al. 1998). The quantity and size distribution of rapping reentrainment emissions from ESPs has been measured. Bush (1984) reported that 14~50% of emissions from cold side ESP was due to rapping. However, the removal of precipitated dust layers by rapping is a complex and poorly understood process, yet it seems probable that rapping reentrainment is a major factor limiting the performance of modern high efficiency precipitators. It was suggested that the dust layer structure might be an important factor that determined the degree of rapping reentrainment (Yamamoto et al. 1998). Therefore a better understanding of the dust layer's physical and electrical characteristics is essential if we are to improve the transfer of dust from the collecting electrodes to the hopper.

REFERENCES

- AHAM (Association of Home Appliances Manufacturers). (1988). *Standard Method for Measuring Performance of Portable Household Electric Cord-Connected Room Air Cleaners*, ANSI-AHAM AC-1-1988, Association of Home Appliances Manufacturers, Chicago.
- ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineer, Inc.). (1992). *Gravimetric and Dust-Spot Procedures for Testing Air-Cleaning Devices Used in General Ventilation for Removing Particulate Matter*, Standard 52.1.
- Awad, M. B., and Castle, G. S. P. (1975). The Efficiency of Electrostatic Precipitators Under Conditions of Corona Quenching, *J. Air Pollut. Control Assoc.* 25(2):172-176.
- Boelter, K. J., and Davidson, J. H. (1997). Ozone Generation by Indoor, Electrostatic Air Cleaners, *Aerosol Sci. Technol.* 27(6):689-708.
- Bohm, J. (1982). *Electrostatic Precipitators*, Elsevier Scientific Publishing Company, New York, pp. 190-196.
- Bush, P. V. (1984). Study of Rapping Reentrainment Emissions from a Pilot-Scale Electrostatic Precipitator, *Environ. Sci. Technol.* 18(9):699-705.
- Davidson, J. H., and McKinney, P. J. (1998). Chemical Vapor Deposition in the Corona Discharge of Electrostatic Air Cleaner, *Aerosol Sci. and Technol.* 29(2):102-110.
- Dorman, R. G. (1974). *Dust Control and Air Cleaning*, Oxford, New York, p. 295.
- Dorsey, J. A., and Davidson, J. H. (1994). Ozone Production in Electrostatic Air Cleaners with Contaminated Electrodes, *IEEE Trans. Ind. Appl.* 30(2):370-376.
- Kanazawa, S., Ohkubo, T., Nomoto, Y., Adachi, T., and Chang, J. S. (1997). Simultaneous Measurements of Wire Electrode Surface Contamination and Corona Discharge Characteristics in an Air-Cleaning Electrostatic Precipitator, *IEEE Trans. Ind. Appl.* 33(1):279-285.

- Kim, S. H., and Lee, K. W. (1998). Influence of Contaminated Discharging Electrode and Collection Plates on Particle Collection Characteristics of ESP, *Proc. 7th International Conference on Electrostatic Precipitation*, Kyongju, Korea, pp. 111–120.
- Lee, J. K., Ku, J. H., Lee, J. E., Kim, S. H., Ahn, Y. C., Shin, J. H., and Choung, S. H. (1998). An Experimental Study of Electrostatic Precipitator Plate Rapping and Reentrainment, *Proc. 7th International Conference on Electrostatic Precipitation*, Kyongju, Korea, pp.155–162.
- McDonald, J. R., Mosley, R. B., and Sparks, L. E. (1980). An Approach for Describing Electrical Characteristics of Precipitated Dust Layers, *J. Air Pollut. Control Assoc.* 30(4):372–376.
- McLean, K. J. (1988). Electrostatic Precipitators, *IEEE Proc.* 135(6):347–362.
- Ogawa, A. (1982). *Separation of Particles from Air and Gases-Volume II*, CRC Press, Inc., Boca Raton, FL, p. 136.
- Perevodchikov, V. I., Kalinin, Y. V., Shapenko, V. N., and Sherbakov, A. V. (1998). Research in Formation of a Dust Layer on Precipitation Electrodes of the Electric Precipitator at an Alternating Polarity Power Supply, *Proc. 7th International Conference on Electrostatic Precipitation*, Kyongju, Korea, pp.171–174.
- Shackelford, J. F., Alexander, W., and Park, J. S. (1994). *CRC Materials Science and Engineering Handbook*, CRC Press, Inc., Boca Raton, FL, p. 565.
- White, H. J. (1974). Resistivity Problem in Electrostatics Precipitation, *J. Air Poll. Cont. Assoc.* 24:313–338.
- Yamamoto, T., Mieno, M., and Shibata, K. (1998). Studies of Rapping Reentrainment from Electrostatic Precipitators, *Proc. 7th International Conference on Electrostatic Precipitation*, Kyongju, Korea, pp.163–170.
- Zhuang, Y., Kim, Y. J., Lee, T. G., and Biswas, P. (2000). Experimental and Theoretical Studies of Ultra-Fine Particle Behavior in Electrostatic Precipitators, *J. Electrostat.* 48:245–260.