Current Density and Efficiency of a Novel Lab ESP for Fine Particles Collection

ZHU Jibao, SHI Yao, ZHANG Xuming, YAN Hui, YAN Keping

(Institute of Environment Pollution Control Technology, College of Environmental and Resource Sciences, Zhejiang University, Hangzhou, 310028, P R China. E-mail: kyan@zju.edu.cn)

Abstract: Understanding the current density will help to improve the ESP's energy consumption and the collection efficiency of fine particles. In this study, corona current density and dust collection efficiency were studied with a laboratory ESP. Dust collection experiments were performed with various electrode distances from 22 mm to 330 mm, and also with a single discharge electrode. Discharge for 40 to 50 seconds with 46 kV voltage, 160 g/m^3 inlet dust concentration and 700 m^3/h flow rate. Ash layer thickness collected on the plate is about 4 mm on average. We observed that the total currents are greatly influenced by the plate-plate gap and electrode distance. The maximum total current was obtained in the 132 mm discharge electrode distance (about half of the plate-plate gap width). The operating voltage range of positive corona is only about half that of the negative corona. Dust layer Accumulation on the plate reduced the total collection current, and increased the spark voltage about 4 kV with 4 mm dust thickness. Increase in the discharge electrode number of the outlet field can improve fine particles collection efficiency.

Keywords: current density; corona; ash; electrostatic precipitation

1 INTRODUCTION

Fine particles have long atmospheric residence time, form the secondary aerosols in the atmosphere and adsorb harmful heavy metals and organic compounds[1.2]. Due to these potential hazards to health, fine particles emission from coal-fired power plants has been a critical issue. Electrostatic precipitators (ESP) are widely used in particulate collection, especially in treating large volume of flue gases. Though the total mass collection efficiency is higher than 99%, most fine particles can penetrate through the ESP, especially the submicron particles. The collection efficiency of fine particles with diameters of less than 2.5 μm ($PM_{2.5}$), hardly match the new standards.

Fine particles have small diameter, low mass but large number. Many phenomena may affect the collection efficiency, such as the insufficient charging, the ionic flow, particle space charge and flow turbulence. Recent studies focused on the fine particles charging and agglomeration. Alternating electric field charger was used to charge particulates by ionic current and the number of particles can diminished under alternating electric field [3.4]. Watanabe designed a new type ESP, the particle mean diameter increased to four times of that at inlet with an electrostatic agglomeration apparatus [5]. Bipolar agglomeration and AC charged plus AC-agglomeration were studied [6-8]. In addition, the ionic flow is also a critical factor, which strongly affected the distribution of charged particles in ESP [9-11]. While the formation and intensity of the ionic flow depend on the current density distribution, structure of the discharge and colleting electrodes of ESP. Mckinney measured the current distribution for barbed plate-to-plane coronas [12]. Correlation between current density and layer structure of fine particles deposition in a lab ESP was studied by Blanchard [13], he measured the current distribution of 100 mm electrode distance. Brocilo studied the effect of electrode geometries on the improvement of collection efficiency for fine particles in ESP, and proposed a model to predict the collection efficiency of fine particles for various geometries of discharge and collecting electrodes[14]. Whereas further studies are still required, in barbed electrode wire-plate precipitator, the current density and fine particles collection efficiency are different with various electrode distances and plate-plate gaps. Investigating the electrode of the ESP can help to find out the critical issue that affects the fine particles collection.

We focus here on the current density of the electrode structure in a lab ESP for fine particles collection. The current density under various electrode distances and plate-plate gaps were measured, and both positive and negative corona discharges are conducted by comparison. Dust collection experiments are conducted under various discharge electrode distances, and the dust collection efficiencies of inlet and outlet field of ESP are calculated with particle size distribution and dust layer thickness.

2 EXPERIMENTAL APPARATUS

This experiment was performed in a circulating lab ESP system as shown in Fig.1 and Fig.2. The ESP is a wire-plate precipitator with 5 fields (length: 1000 mm, height: 1000 mm in total). Voltage-current (V-I) characteristics of the ESP with various plate-plate gaps (*g*=200 mm, 250 mm, 300 mm and 350 mm) were measured. The total collection surface of the plates is 1.38 m^2. The discharge electrode (DE) is a saw type, the fixed distance between tips on the discharge electrode s is 22 mm. Current density and dust collection were conducted with various electrode distances (*d*=22 mm, 44 mm, 88 mm, 176 mm and 330 mm) and single electrode as shown in Table1. Flow rate of the ESP system can be adjusted from 0 to 1000

m^3/h. Positive and negative DC voltage was used. All experiments were conducted at the temperature of about 20℃ in air.

Coal-fired plant fly ash was used as the collection dust in this experiment. The volume mean diameter of this dust is $d_{p,50}$=8.2μm and dust specific resistivity is $\rho_d = 7.1\times10^7$ Ω·cm in air. Dust collection experiments are performed with various electrode distances from 22 mm to 330 mm, and also with a single discharge electrode. Discharge for 40 to 50 seconds with 46 kV voltage, 160 g/m^3 inlet dust concentration and 700 m^3/h flow rate. The gas velocity in the ESP is 0.78 m/s and the time of gas flow going a cycle of the lab ESP system is 2.8 s. Ash layer thickness on the plate is about 4 mm on average. We took samples from the inlet and outlet sides of the plate with a steel tube after the thickness of ash layer was measured with micrometer, and analyzed the size distribution with Malvern laser diffraction analyzer. The density of the dust on the plate was calculated with the mass and thickness.

Table 1 Distance and number of discharge electrode

d [mm]	22	44	88	176	330
N_{DE}	31	16	8	4	3

d: Discharge electrode distance N_{DE}: Discharge electrode number

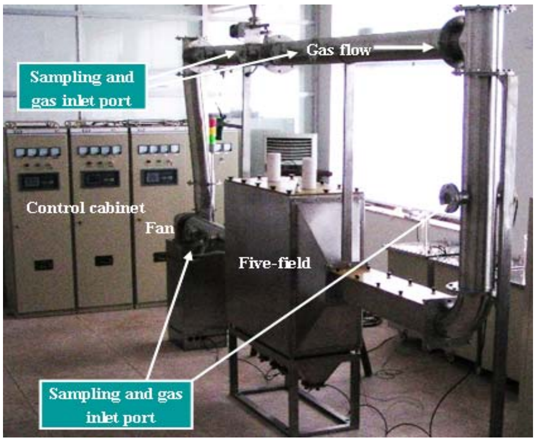

Fig. 1 Laboratory ESP system

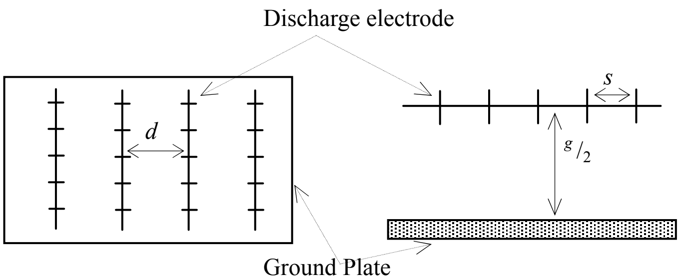

Fig. 2 Diagram of dimensional variables plate to electrode in ESP

3 RESULTS

3.1 Current density of various plate-plate gaps

For a given discharge electrode distance d 22 mm, the effect of various plate-plate gaps on the current density is shown in Fig.3. The current density profiles indicate that the corona current reduced dramatically, increasing the plate-plate gap from 100 mm to 300 mm. When the plate-plate gap is 200 mm, 250 mm, 300 mm, the current density is 3.2 mA/m^2, 0.6 mA/m^2, 0.2 mA/m^2, respectively and the breakdown voltage is 44 kV, 57 kV, 65 kV, respectively. Under the same corona current, a larger plate-plate gap can generate a higher voltage and has a larger range of operating voltage. Larger plate-plate gap ESP can save a lot of costs, but the electric power system must match the high voltage and other insulation factors need further consideration. In order to get proper current density and high electric field, the dust collection experiments were conducted with 250 mm plate-plate gap.

3.2 Comparison between positive and negative corona discharge

Positive and negative corona discharge was conducted in this lab ESP with 22 mm discharge electrode distance and 200 mm plate-plate gap. The voltage-current (V-I) curves presented in Fig.4 show that the onset voltage of positive corona is higher than that of negative corona. The breakdown voltage of positive corona is 33 kV, and negative corona is 44 kV. As the V-I curves show, the operating voltage range of positive corona is only about half that of the negative corona. In order to get higher operating voltage, negative corona is better than positive corona for dust collection of ESP. The current density of positive corona is almost three times that of the negative corona discharge. This indicates that positive corona discharge We can smell the ozone with the positive corona discharge, but no ozone was smelled with the negative corona in this lab ESP can generate more ozone, but the concentration needs to measure in the latter experiment.

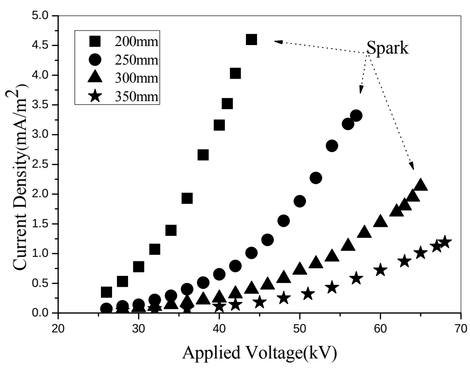

Fig. 3 V-I curves of various plate-plate gaps

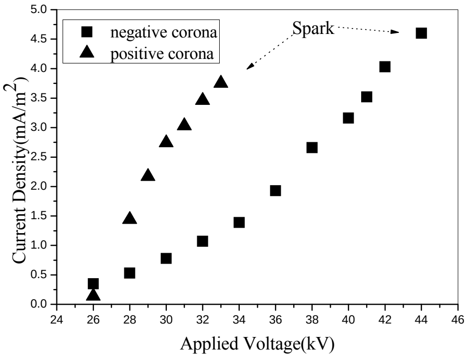

Fig. 4 V-I curves of positive and negative corona

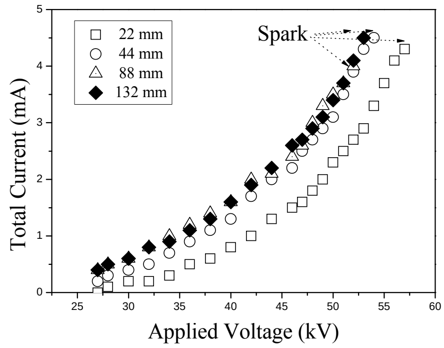

Fig. 5 V-I curves from 22 mm to 132 mm distance

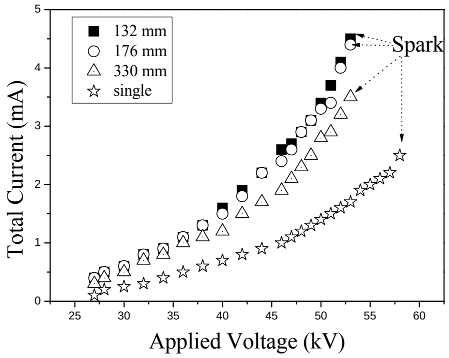

Fig. 6 V-I curves from 132mm to 330mm distance

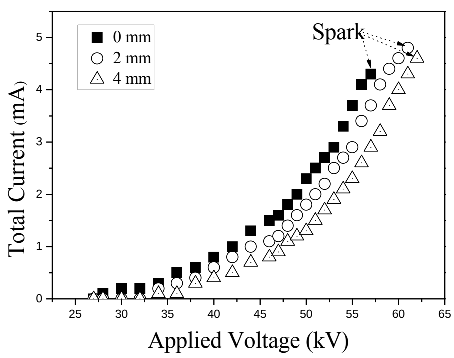

Fig. 7 V-I curves of 22 mm distance with dust on plate

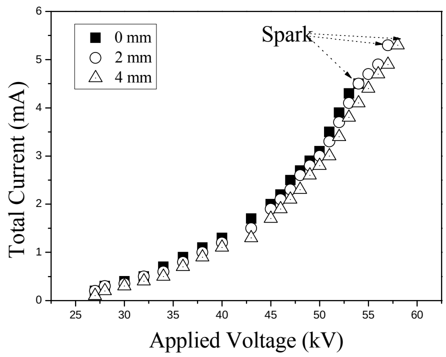

Fig. 8 V-I curves of 44 mm distance with dust on plate

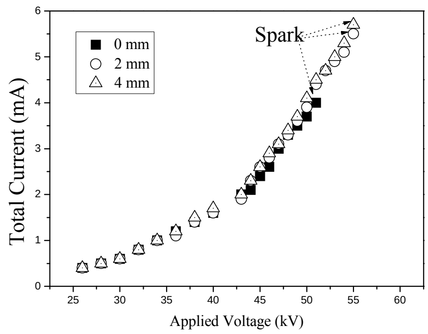

Fig. 9 V-I curves of 88 mm distance with dust on plate

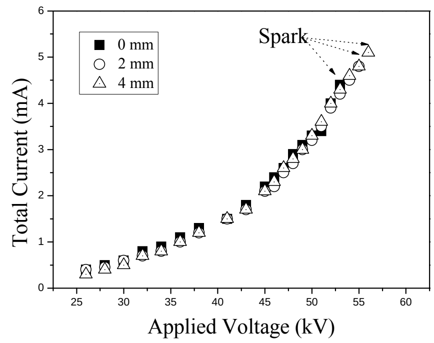

Fig. 10 V-I curves of 176 mm distance with dust on plate

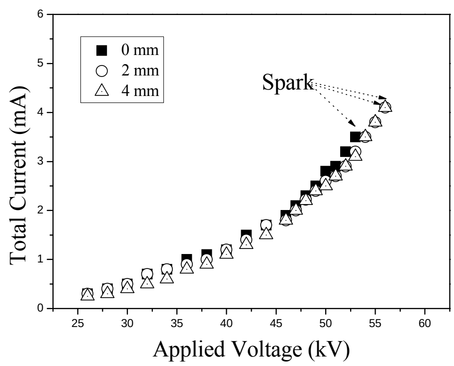

Fig. 11 V-I curves of 330 mm distance with dust on plate

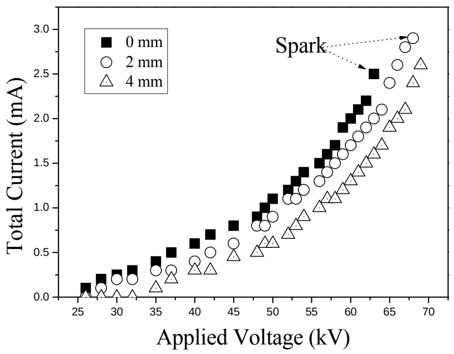

Fig. 12 V-I curves of single electrode with dust on plate

3.3 Current density of various discharge electrode distances

Due to the non-uniformity of current density in Wire-plate ESP, it is necessary to study the corona current density of a new wire-plate precipitator. With negative DC power, experiments were performed with various discharge electrode distances from 22 mm to 330 mm, and also a single discharge electrode shown in Fig. 5 and Fig. 6. The results indicate that the ESP with various distances has different onset corona voltages. The total current increases with an increasing distance from 22 mm to 132 mm, while decreases with an increasing distance from 132 to 330 mm. When the ratio of the discharge electrode distance to the half plate-plate gap width is about 1:1 (132 mm distance), the maximum current was obtained at a given voltage (4.5 mA at V = 52 kV). The lowest current was obtained with the single discharge electrode at a given voltage (1.2 mA at V = 52 kV).

With the dust layer deposition, the total currents reduced as shown in Fig. 7 to Fig. 12. The total current of 22 mm electrode distance drops about 0.2 mA and 0.4 mA at the same voltage with 2 mm and 4 mm dust layer collected on. The same current drop was observed with single discharge electrode. The extent of this total current reduction decreases with the electrode distance increasing from 22 mm to 88 mm. In contrast, the extent of the total current reduction increases with the electrode distance increasing from 176 mm to 330 mm and single electrode. Almost no total current drop was observed when the electrode distance is132 mm (almost half the plate-plate gap width). These V-I curves show that dust layer accumulation on the plate reduced the collection current. The spark voltage increased about 4kV with 4 mm thickness dust on the plate.

3.4 Dust collection efficiency

Dust collection experiments were conducted with various electrode distances in this study. The mass distribution of the dust as follow: $PM_{2.5}$ is 12.05 %, $PM_{2.5\text{-}10}$ is 45.34% and $PM_{>10}$ is 42.61%. The dust collection efficiency of this experiment was calculated by the mass balance as follows:

With 125 g dust load, we discharge for 40 seconds. In this circulating system, the gas flow goes through the ESP for 15 times in 40 seconds. Equation 1) shows the dust collection pattern of each cycle with 125 g dust load in 40 seconds. When we added 40 times of 125 g dust, the ash layer thickness on the plate is about 4 mm on average. If ignore the influence of dust layer on the plate, we can assume that each 125 g dust load has the same collection efficiency.

$$\eta_m = 1-(1-\eta_1)(1-\eta_2)\cdots(1-\eta_{15}) \quad (1)$$

Where η_i is the collection efficiency of different cycle of gas flow with 125 g dust load in 40 seconds, C_{out} is the dust concentration of outlet, C_{in} is the dust concentration of inlet, m_p is the mass of dust on the plate (g), m_h is the mass of dust in the hoppers (g), η_m is the collection efficiency of this lab ESP, m_0 is the total added mass of dust (g).

In five fields ESP, the mass of collected dust on plate was divided into five parts. The mass of dust on the plate were calculated by the dust layer thickness and dust accumulation density. The grade collection efficiency of inlet and outlet fields can be calculated with the dust layer thickness and particle size distribution by equations (2):

$$\eta_{grade} = \frac{\Delta m_p \cdot G_{ip}}{m_0 \cdot G_{i0}} \times 100\% + \frac{m_h \cdot G_{ih}}{m_0 \cdot G_{i0}} \times 100\% \quad (2)$$

$$\eta_p = \frac{\Delta m_p \cdot G_{ip}}{m_0 \cdot G_{i0}} \times 100\% \quad (3)$$

Where m_p is the mass of collected dust on the plate (g), Δm_p is the mass of colleted dust on different electric field (g), S is the inlet or outlet plate area (m^2), h is the dust thickness on the plate (m), ρ is the density of dust layer deposited on the plate (g/m^3), η_{grade} is the grade collection efficiency of the total added dust, G_{ip}, G_{ih}, G_{i0} are the percent of $PM_{2.5}$, $PM_{2.5\text{-}10}$ and $PM_{>10}$ on the plate, hoppers and original added dust, respectively, m_0 is the total added mass of dust (g), η_p is the grade collection efficiency on the plate.

We focus here on the dust layer collected on the plate without rapping, and the grade collection efficiency on the plate was calculated by equation (3).The inlet field dust collection efficiency on the plate was shown in Fig.13. The results show that the collection efficiencies of $PM_{2.5}$ with various electrode distances are all about 47%, and the distance between discharge electrodes has little effect on the collection efficiency. While the collection efficiencies of $PM_{2.5\text{-}10}$ with various electrode distances are all less than 38%. In view of the particles above 10 μm, the collection efficiency with 22 mm discharge electrode distance is about 66%, while others are all below 57% with other distances. The lower collection efficiencies of the distance of 88 mm and 176 mm indicate that high current is unfavorable to large particle collection. The outlet field dust collection efficiency on the plate was shown in Fig.14. With 22 mm electrode distance and single electrode, the collection efficiencies of $PM_{2.5}$ are about 11%, while with the distance of 88 and 176 mm, the collection efficiencies are 5.3% and 8.5%, respectively. The collection efficiencies of $PM_{2.5\text{-}10}$ with various distances are below 7.5%, which indicates that about half of the $PM_{2.5\text{-}10}$ was collected in the middle fields. Little particles above 10μm were collected in the outlet field.

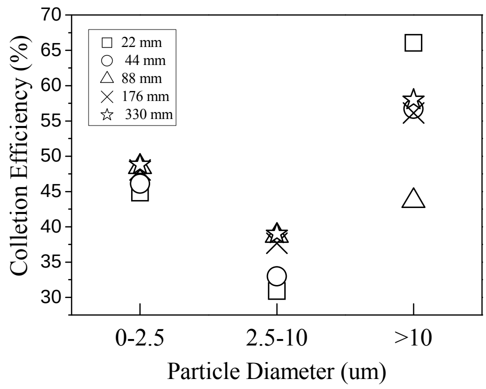

Fig. 13 Inlet dust collection efficiency on the plate

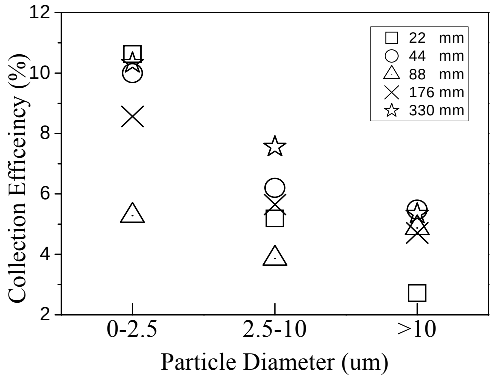

Fig. 14 Outlet dust collection efficiency on the plate

Compared the inlet field with the outlet field, the results indicate that about half of the fine particles were collected in the inlet field, and the distance between discharge electrodes has little effect on the efficiency. While in the outlet field, increase in the number of the discharge electrodes can improve the fine particles collection efficiency

4 CONCLUSIONS

This paper presents the results of current density and the grade efficiency of a lab ESP with various electrode distances. The results demonstrate that the total currents are greatly influenced by the plate-plate gap and electrode distance. The maximum total current was obtained with the 132 mm distance of discharge electrode (about half the plate-plate gap width). Dust layer deposition on the plate reduced the total collection current, and increased the spark voltage about 4 kV with 4 mm dust thickness. The practical operating voltage range of positive corona is only about half that of the negative corona.

Almost half of the fine particles were collected in the inlet field, and the distance between discharge electrodes has little effect on the efficiency. Optimization of the fine particles efficiency is possible by appropriate position of the electrode distance. Increase in the number of the discharge electrodes of the outlet field can improve fine particles collection efficiency.

ACKNOWLEDGEMENTS

This project was supported by the National Natural Science Foundation of China (No. 20776131) and Specialized Research Fund for the Doctoral Program of Higher Education Ministry of Education of China (No. 20070335194).

REFERENCES

1. J. Ondov, A. Wexler, Where do particulate toxins reside? An improved paradigm for the structure and dynamics of the urban mid-Atlantic aerosol. Environmental science and Technology. 1998, 32: 2547-2555.
2. P. Biswas, C. Y. Wu, Control of toxic metal emission from combustors using sorbents: A review. Journal of the Air &Waste Management Association. 1998, 48: 113-127.
3. M. Lackowski, K. Adamiak, A. Jaworek, Electrostatic charging of particulates by ionic current in alternating electric field, Powder Technology. 2003, 135-136: 243-249.
4. M. Lackowski, A. Jaworek, A. Krupa, Current-voltage characteristics of alternating electric field charger, J. Electrostatics. 2003, 58: 77-89.
5. T. Watanabe, F. Tochikubo, Y. Koizumi, Submicron particle agglomeration by an electrostatic agglomerator, J. Electrostatics. 1995, 34: 367-383.
6. Laitinen, J. Hautanen, J. Keskinen, Bipolar charged aerosol agglomeration with alternating electric field in laminar gas flow, J. Electrostatics. 1996, 38: 303-315.
7. Zukeran, Y. Ikeda, Y. Ehara, T. Takahashi, Agglomeration of Particles by ac corona discharge, Electrical Engineering in Japan. 2000, 130: 30-36.
8. Y. Koizumi, M. Kawamura, F. Tochikubo, Estimation of the agglomeration coefficient of bipolar-charged aerosol particles, J. Electrostatics. 2000, 48: 93-101.
9. J. H. Davidson, P. J. Mckinney, EHD Flow Visualization in the Wire-Plate and Barbed Plate Electrostatic Precipitator, IEEE Transactions on industry applications. 1991, 27: 154-160.
10. Blanchard, L. M. Dumitran, P. Atten, Effect of electro-aero-dynamically induced secondary flow on transport of fine particles in an electrostatic precipitator, J. Electrostatics. 2001, 51-52: 212-217.
11. J. Podlinski, A. Niewulis, J. Mizeraczyk, P. Atten, ESP performance for various dust densities, J. Electrostatics. 2008, 66: 246-253.
12. P. J. Mckinney, J.H. Davidson, D.M. Leone, Current distribution for barbed plate-to-plane coronas, IEEE Transaction on Industry application., 1992, 28: 1424-1431.
13. Blanchard, P. Atten, and L. M. Dumitran, Correlation between current density and layer structure for fine particle deposition in a laboratory electrostatic precipitator, IEEE Transaction on Industry application. 2002, 38: 832-839.

14. Brocilo, Electrode geometry effects on the collection efficiency of submicron and ultrafine dust particles in wire-plate electrostatic precipitators, Doctor thesis. McMaster university, Hamilton, Ontario 2003.