Effect of ionic flow on the electrostatic precipitation of nanoparticles

Alessandro Estarque de Oliveira, Vádila Giovana Guerra
Department of Chemical Engineering
Federal University of São Carlos - UFSCar
São Carlos, Brazil
alessandroestarque@gmail.com

***Abstract* — The objective of this work was use the concept of electrohydrodynamic number to evaluate the influence of the ionic wind on the primary flow of the gas and its effect on the electrostatic precipitation of nanoparticles in order to consolidate the knowledge of this effect. Prevalence of electric forces at low gas velocities led the particle collection under these conditions. It was necessary the evaluation of combined effects with other variables besides the electrohydrodynamic number when the gas velocity was changed.**

Keywords* — *Electrostatic precipitation; nanoparticulate; ESP; electrostatics; electrohydrodinamic flow

I. Introduction

The extensive use of electrostatic precipitators (ESPs) is due to their high collection efficiency in the gas-solid separation. Reduction in the emission of solid residues in the atmosphere [1] and recovery of high added value materials [2] are common applications of these devices.

Into the ESP, the flow of ions and electrons in the space between discharge and collection electrodes results in a phenomenon named ionic wind or secondary flow, which forms vortexes and local turbulence and influences on the gas flow – the primary flow [3]. Several studies have evaluated the influence of the ionic wind on the gas flow in ESPs, experimentally by particle image velocimetry [4, 5] or by the modelling of the process [6, 7], all of them using the concept of electrohydrodynamic flow number (EHD). The Institute of Electrical and Electronics Engineers recommends the following definition [8]:

$$EHD = I_0 \; L^3 / (\rho_f \; z_f \; \nu_f^2 \; A) \tag{1}$$

in which I_0 is the reference current (in μA), L is the characteristic length, ρ_f and ν_f are respectively the density and kinematic viscosity of the gas, z_f is the ion mobility and A is the superficial area based on L.

In order to verify the influence of the ionic wind on the primary flow, the ratio EHD/Re^2 is used, in which the Reynolds number, Re, is based on L and is given for [4]:

$$Re = u_0 \; L / \nu_f \tag{2}$$

in which u_0 is the superficial velocity of the gas in the duct.

The authors are grateful to CNPq and PPGEQ – UFSCar for the financial sponsoring.

In other terms, the ratio EHD/Re^2 indicates the relative influence of the electric force in relation to the viscous and inertial forces. According to Podliński *et al.* [9], the secondary flow exerts strong influence on the gas flow in wire-plate ESPs at EHD/Re^2 much higher than 1, which means that the electric force is highly enough in relation to the other forces to disturb the flow pattern.

ESPs do not offer 100% of efficiency to collect nanoparticles, which size is commercially interesting, but harmful to health [2, 10, 11]. In this way, this work intended to use the parameter EHD/Re^2 to evaluate the relation between the primary and the secondary flows and its effect on the collection efficiency of nanoparticles by a wire-plate ESP. Therefore, this study can contribute to the technology of electrostatic precipitation of nanoparticulate.

II. Materials and Methods

Fig. 1 shows a scheme of the experimental system used in the tests and Fig. 2 shows a scheme of the ESP. The wire-plate ESP was made of acrylic and contained two copper plates with 0.10 m of height, 0.30 m of length and plate spacing of 0.04 m. There was eight discharge electrodes of stainless steel with $3x10^{-4}$ mm of diameter and spacing of 0.04 m. They were disposed in the symmetry axis of the duct.

In the tests, a compressor injected air at 25ºC and 92 kPa in the system under controlled flow rate. The air passed though air filters and an association of membranes to retain impurities and humidity. An aerosol generator (TSI, model 3079) injected compressed air at 100 NL/h to atomize an aqueous solution of KCl. The particulate passed through a diffusion dryer (TSI, model 3062) and it was mixed with the main gas stream. A high voltage power supply (Spellman, model SL30PN300) produced a high voltage electric current in the discharge electrodes. Radioactive sources (Kr-85 and Am-241) neutralized particle charges in order to avoid disturbances in the concentration measurements.

The aerosol concentration was measured by a Scanning Mobility Particle Sizer (TSI, model 3936) composed of an Electrostatic Classifier (model 3080) attached to a Differential Mobility Analyzer (DMA) and an Ultrafine Condensation Particle Counter (UCPC, model 3776). The Electrostatic Classifier separated the particles in the aerosol by applying different voltages and moving them along the DMA in according with their electrical mobility – its ability to move across an electric field [10]. Then, the selected particles passed through the UCPC, in which an optical sensor detected the flow rate of the particles of a giver diameter in the sample. Therefore, the SMPS measured the equivalent electrical mobility diameter of the aerosol.

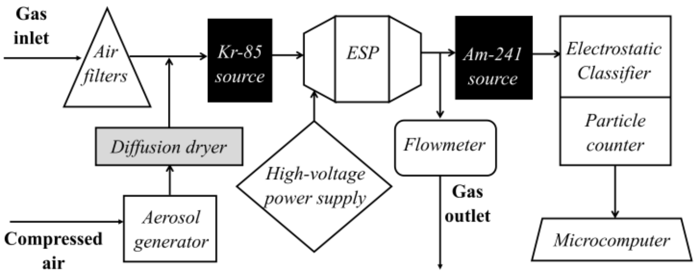

Fig. 1. *Scheme of the experimental system*

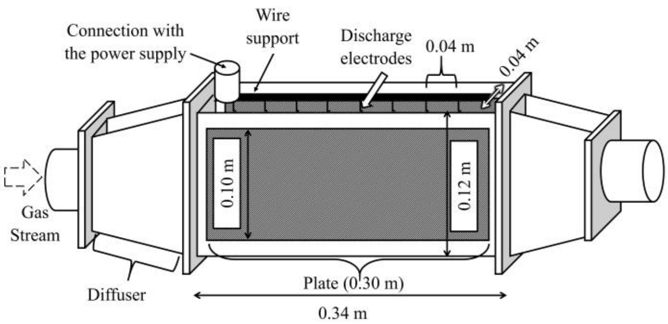

Fig. 2. *Scheme of the ESP used in the tests*

Table 1 exhibits the operational conditions used in the tests and the parameters of particle size distribution (median and geometric standard deviation, σ) obtained for each test.

TABLE I. NOMENCLATURE OF THE TESTS AND CONDITIONS USED

Test	Gas velocity (cm/s)	Voltage (kV)	Median (nm)	σ
1a	1.65	-8.0	34.87 ± 0.17	1.86 ± 0.00
2a	1.65	-8.1	34.41 ± 0.20	1.85 ± 0.01
3a	1.65	-8.2	34.77 ± 0.12	1.86 ± 0.01
1b	3.32	-8.0	36.88 ± 0.31	1.92 ± 0.01
2b	3.32	-8.1	36.46 ± 0.17	1.89 ± 0.01
3b	3.32	-8.2	36.82 ± 0.25	1.91 ± 0.01
1c	6.57	-8.0	39.99 ± 0.59	1.94 ± 0.01
2c	6.57	-8.1	39.74 ± 0.18	1.94 ± 0.01
3c	6.57	-8.2	41.02 ± 1.52	1.88 ± 0.04
1d	9.82	-8.0	41.98 ± 0.16	1.94 ± 0.01
2d	9.82	-8.1	42.10 ± 0.24	1.95 ± 0.00
3d	9.82	-8.2	41.06 ± 0.30	1.95 ± 0.00
1e	19.9	-8.0	46.44 ± 0.76	1.93 ± 0.03
2e	19.9	-8.1	46.20 ± 0.26	1.93 ± 0.02
3e	19.9	-8.2	47.48 ± 0.47	1.92 ± 0.03

Values of gas velocity are presented in “cm/s” in the present work due to the range of low velocities used. In fact, the range of velocities evaluated is not usually investigated in ESPs, but is known that it provides enhancement of the diffusional mechanism in the collection of nanoparticles by filters, for example [10]. In turn, diffusional charging is the main mechanism to charge particles less than 200 nm in ESPs [3].

In order to maintain the particle size distribution for each gas velocity, a KCl solution of different concentration was prepared, as follows: 0.5, 1.0, 2.0, 3.0, and 6.0 g/L respectively for 1.65, 3.32, 6.57, 9.82, and 19.9 cm/s. Therefore, particle concentrations in the order of 10^{10} particles/m³ were obtained for all the tests.

The electric current obtained by the power supply was equal to 0.01, 0.02, and 0.04 mA for tests with applied voltage respectively of -8.0, -8.1, and -8.2 kV. In fact, the corona onset voltage for all the tests was equal to -8.0 kV.

The humidity of the air was controlled and maintained below of 20% for all tests.

The tests were performed in triplicate. The experimental grade collection efficiency η was calculated from the relation between the particle concentration in the inlet (c_i) and the outlet (c_o) of the ESP for each diameter, as follows:

$$\eta\ (\%) = 100\ .\ (c_i - c_o)\ /\ c_i \qquad (3)$$

The overall collection efficiency of the equipment for each test was also calculated by (3) with the total concentration measured by the SMPS in the inlet and the outlet of the ESP. The device converted particle number concentration in mass concentration by feeding the software with the particle density of KCl, equal to 1,988 kg/m³ [12].

The characteristic length considered in the calculations of the EHD/Re² was the distance between the plates (L = 0.04 m; A = 0.06 m²).

III. Results and Discussion

Fig. 3 presents the EHD/Re² values calculated for the gas velocities and voltages used in the tests. It was verified that the increase of EHD/Re² with the enhancement of voltage at a fixed velocity was greater for the lower velocity used (1.65 cm/s). In accordance with this increase, there is enhancement of vortexes and acceleration of the gas due to its interaction with the ionic flow originated between discharge and collection electrodes [4, 5]. It was also noticed that the ratio decreased with the increase of gas velocity. In this case, the primary flow is less affected by the ionic wind [6], since there was a decrease of the electric force influence on the flow pattern in relation to the viscous and inertial forces, although there may be eventual turbulence generation if the gas velocity is high [4]. In addition, it was verified that different combinations of voltage and gas velocity resulted in similar values of EHD/Re², like tests 1a and 3b, resulting in a value close to 150 and tests 1b and 3c, with value close to 38.

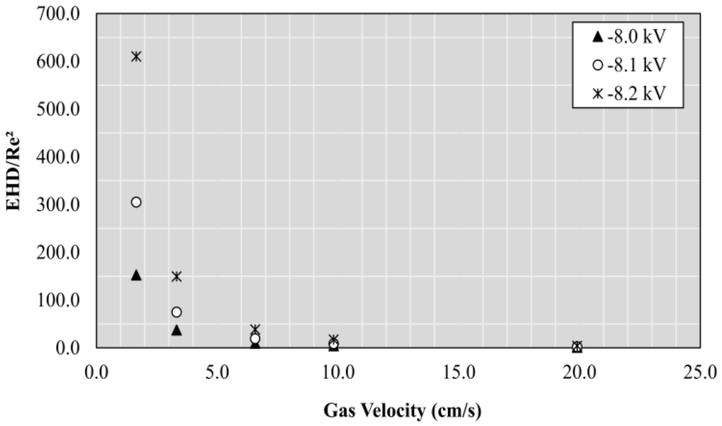

Fig. 3. *EHD/Re² ratios obtained in the tests*

The results of efficiency tests for each combination of voltage and gas velocity used – and named in according with Table 1 – are presented in Fig. 4. It was observed that there was a significant difference between the grade efficiency curves with the increment from -8.0 to -8.1 kV under the lower gas velocity (a). Also, this difference reduced with the increase of velocity. This is in accordance with that verified in Fig. 3, in which the ratio EHD/Re² enhanced significantly with the increase of voltage under the lower velocity and indicates an overlapping of the electric force on the viscous force in this case. The generation of higher electric field ionizes a greater number of gas molecules, enhancing the number of collisions between ions and particles and the charge transfer between them. Hence, it is greater the probability of the charged particles to move towards the collection plates and be collected by them [3, 10]. Additionally, it was verified an anomalous tendency of the grade efficiency curve of the test 1b (b), which presented several peaks of efficiency for diameters of 20, 50, and 115 nm. It is possible that the local vortexes formed due the interaction between the ion flow and the gas stream, associated with the effect of particle size on the electrical mobility and on the number of charges acquired in its volume, have led these results in this configuration of operational conditions.

It was noticed that the test 3b (-8.2 kV and 3.32 cm/s) resulted in higher efficiencies than the test 1a (-8.0 kV and 1.65 cm/s), even with similar EHD/Re² (close to 150). The same phenomena occurred between tests 3c (-8.2 kV and 6.57 cm/s) and 1b (-8.0 kV and 3.32 cm/s), with EHD/Re² close to 38. In these situations, the increment of both the variables resulted in improvement of the process. In addition, for tests at 9.82 and 19.9 cm/s (d, e), the increase of velocity did not only decreased the influence of the electric force on the efficiency, but also decreased the residence time of the particles in the device, affecting their capture by the plates. In order to understand this phenomenon, results of overall efficiency of the device for each test, calculated by the definition expressed in (3), are showed in Fig. 5 for different EHD/Re² evaluated in this work. Each curve is referred to a different residence time, corresponding to the different gas velocities used. The residence time was obtained by the ratio between the volume of the ESP (0.0012 m³) and the volumetric gas flow rate for each gas velocity. It is more clear that, although some tests have similar values of

EHD/Re², differences in the gas residence time led to completely different overall efficiencies. For example, for tests 3b and 1a (EHD/Re² close to 150), the efficiency for the first was 99.81%, while the latter resulted in overall efficiency of 38.08%. This was a consequence of that observed in the grade efficiency curves of Fig. 4. The tendencies of the curves also demonstrates the effect of the electric force on the collection efficiency at a fixed velocity for different residence times: the higher the residence time, the higher the increase in overall efficiency for the same increment of voltage, since EHD/Re² is also higher. However, for the two lowest residence times evaluated, equal to 3.05 and 1.50 s (corresponding to the gas velocities of 9.82 and 19.9 cm/s), the tendencies changed, indicating the decrease of the ionic wind influence on the primary flow and consequently on the collection efficiency.

In fact, the particle charged into the ESP is subject to the viscous force of the gas and the electrical force existing between the discharge and the collection electrodes. The balance between these two forces results in the terminal velocity of the particle – the migration velocity – with which the particle moves through the collection electrodes. The increase of gas velocity reduces the probability of the charged particle to move towards the collection electrode with its migration velocity and be collected before it pass through the ESP, carried by the gas flow, which decreases the collection efficiency [3, 10].

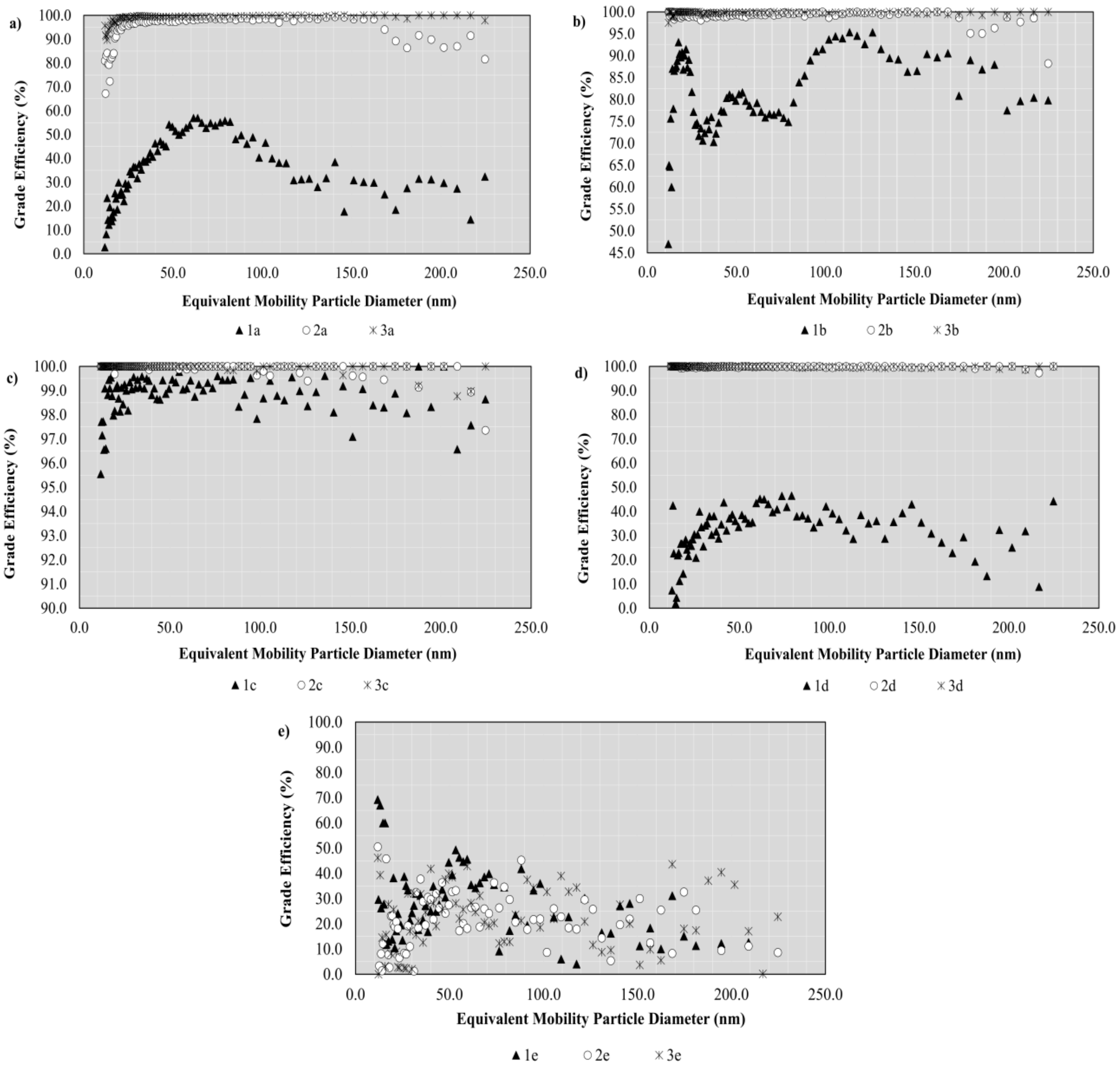

Fig. 4. *Grade efficiencies of the tests at 1.65 (a), 3.32 (b), 6.57 (c), 9.82 (d), 19.9 cm/s (e), under different voltages*

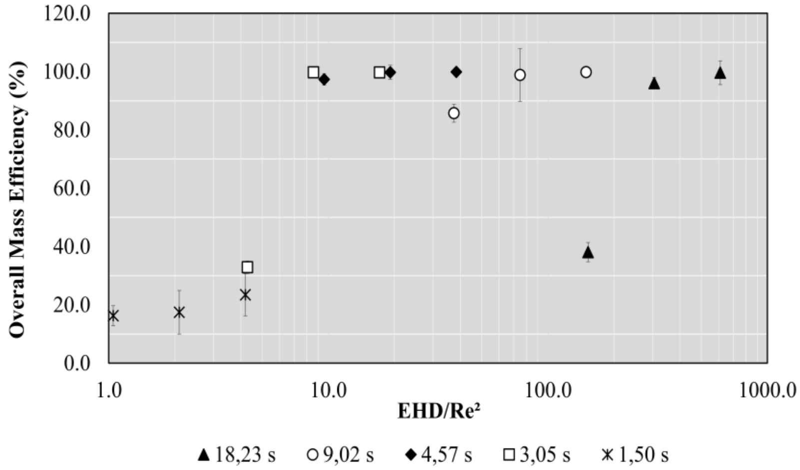

Fig. 5. *Overall efficiencies of the tests in relation to EHD/Re² for different residence times*

Studies on nanoparticle collection by ESPs evaluated the influence of the gas velocity on the collection efficiency in terms of particle residence time [13-15]. However, the effect of the ionic wind on the primary flow was not taken into account in the abovementioned studies, even though it has been demonstrated that the relative influence of the electric force in relation to the inertial and viscous forces could disturb the gas flow, forming vortexes and local turbulence and consequently affecting the particle trajectory [4-7]. Indeed, according to Podliński *et al.* [9], the secondary flow exerts strong influence on the gas flow in wire-plate ESPs at EHD/Re^2 much higher than 1, which was the case for almost all tests in this work. Therefore, the present results demonstrate that both the factors – the residence time and the electro-fluid dynamics – must be analyzed in order to evaluate the effect of gas velocity on the process of particle collection by ESPs.

IV. Conclusions

Analysis and discussion of results obtained by the experimental procedure performed in this work allowed to conclude that the influence of the ionic wind on the gas stream was prominent for low gas velocities and resulted in increase of collection efficiency with the increase of applied voltage. The EHD/Re^2 ratio was useful to describe the relative influence of the electric force on the process in relation to the inertial and viscous forces, but the influence of the gas velocity on the ESP efficiency was also due to the residence time, which was reduced with the increase of gas velocity, decreasing the collection efficiency.

References

[1] T. Nussbaumer, and A. Lauber, “Monitoring the availability of electrostatic precipitators (ESP) in automated biomass combustion plants”. Biomass Bioenergy, vol. 89, pp. 24-30, 2016.

[2] A. Lähde, I. Koshevoy, T. Karhunen, T. Torvela, T. A. Pakkanen, and J. Jokiniemi, “Aerosol-assisted synthesis of gold nanoparticles”. J. Nanopart. Res., vol. 16, pp. 2716-2723, 2014.

[3] K. Parker, “Electrical operation of electrostatic precipitators”. London: The Institution of Electrical Engineers, 2007.

[4] Y. N. Chun, J. S. Chang, A. A. Berezin, and J. Mizeraczyk, “Numerical modeling of near corona wire electrohydrodynamic flow in a wire-plate electrostatic precipitator”. IEEE Trans. Dielectr. Electr. Insul., vol. 14, n. 1, pp. 119-214, 2007.

[5] Z. Ning, J. Podlinski, X. Shen, S. Li, S. Wang, H. Ping, and K. Yan, “Electrode geometry optimization in wire-plate electrostatic precipitator and its impact on collection efficiency”. J. Electrostat., vol. 80, pp. 76-84, 2016.

[6] H. Fujishima, Y. Morita, M. Okubo, and T. Yamamoto, “Numerical simulation of three-dimensional electrohydrodynamics of spiked-electrode electrostatic precipitators”. IEEE Trans. Dielectr. Electr. Insul., vol. 13, n. 1, pp. 160-167, 2006.

[7] Q. Lancereau, J. Roux, and J. L. Achard, “Electrohydrodynamic flow regimes in a cylindrical electrostatic precipitator”. IEEE Trans. Dielectr. Electr. Insul., vol. 20, n. 4, pp. 1409-1420, 2013.

[8] INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS - IEEE. “Recommended international standard for dimensionless parameters used in electrohydrodynamics”. IEEE Trans. Dielectr. Electr. Insul., vol. 10, n. 1, pp. 3-6, 2003.

[9] J. Podliński, J. Dekowski, J. Mizeraczyk, D. Brocilo, J. S. Chang, “Electrohydrodynamic gas flow in a positive polarity wire-plate electrostatic precipitator and the related dust particle collection efficiency”. J. Electrostat., vol. 64, pp. 259–262, 2006.

[10] W. C. Hinds, “Aerosol technology: properties, behavior, and measurement of airborne particles”, 2nd ed. New York: John Wiley, 1998.

[11] B. A. Maher, I. A. M. Ahmed, V. Karloukovski, D. A. Maclaren, P. G. Foulds, D. Allosop, D. M. A. Mann, R. T. Jardón, and L. C. Garciduenas, “Magnetite pollution nanoparticles in the human brain”. Proceedings of the National Academy of Sciences of the United States of America (PNAS), 2016.

[12] J. A. Dean, “Lange’s handbook of chemistry”, 15th ed. New York: McGraw-Hill, 1999.

[13] Y. Zhuang, Y. J. Kim, T. G. Lee, P. Biswas, “Experimental and theoretical studies of ultra-fine particle behaviour in electrostatic precipitators”. J. Electrostat., vol. 48, pp. 245-260, 2000.

[14] C. W. Lin, S. H. Huang, Y. M. Kuo, K. N. Chang, C. S. Wu, C. C. Chen, From electrostatic precipitation to nanoparticle generation, J. Aerosol Sci., 51: 57–65, 2012.

[15] L. Morawska, V. Agranovski, Z. Ristovski, M. Jamriska, “Effect of face velocity and the nature of aerosol on the collection of submicrometer particles by electrostatic precipitator”. Indoor Air, vol. 12, pp. 129-137, 2002.