Effect of Face Velocity and the Nature of Aerosol on the Collection of Submicrometer Particles by Electrostatic Precipitator

L. MORAWSKA, V. AGRANOVSKI, Z. RISTOVSKI, M. JAMRISKA

Centre for Medical and Health Physics, Queensland University of Technology, 2 George St, PO Box 2434, Brisbane, QLD 4001, Australia, Tel: +61 7 3864 2616, Fax: + 61 7 3864 1521, email: v.agranovski@ qut.edu.au

Practical Implications

This paper presents results obtained on the evaluation of collection efficiency of a two-stage pilot-scale ESP with a focus on environmental tobacco smoke, one of the most common combustion product. The data presented can be used in compilation of a comprehensive experimental database that could be used in developing and/or evaluating the precipitator models and on which precipitator designers/manufacturers can base the design of new installations.

Abstract. Despite the electrostatic collection of aerosol particles is one of the most widely used air cleaning methods, there have not been sufficient amount of effort devoted to investigate its performance in the full range of operating conditions. This paper reports results of the tests of a two-stage electrostatic precipitator (ESP) conducted in the particle size range of 0.018 - 1.2μm over a range of flow rates using NaCl and Environmental Tobacco Smoke (ETS) test aerosols. The total collection efficiency of the precipitator was found to increase with an increase in the count median diameter (CMD) of the particles, to have polynomial dependence on flow rate and no significant dependence on the type of test aerosol. The fractional efficiency of the precipitator was found to be dependent on flow rate. However, the "critical" particle size of about 1.2 μm was found to exist when the fractional collection efficiency becomes independent of flow rate. For submicrometer particles, the collection efficiency was found to be independent of particle size at flow rates below 560 $L.s^{-1}$. A minimum in the efficiency was observed in the 0.1 to 0.45 μm particle size range and for particles smaller than about 0.02 μm.

Key words Air cleaning; Electrostatic precipitator; Efficiency tests; Submicrometer particles; Particle size distribution

Introduction

In the control of particle emissions to the atmosphere, the emphasis has been on reducing the mass of pollutant discharged, without attention to other particle characteristics such as chemical composition or particle size. Despite the fact that particles in the submicrometer size range constitute a smaller fraction by weight of the total suspended particle matter in typical particle emissions, it is widely recognised that particles in this size range could have greater environmental impact than larger particles. Submicrometer particles are considered potentially hazardous to health due to their high probability of deposition in deeper parts of the respiratory tract. It is known that they are carriers of heavy metals and some mutagenic compounds that are adsorbed on the particles and as a result represent a serious health hazard if inhaled. The long retention time of submicrometer particles in the atmosphere makes them a more significant control problem than of the larger particles.

The increasing demands on control of fine (defined usually as particles with aerodynamic diameters less than 2.5 μm) and ultra-fine (particles with aerodynamic diameters less than 0.1 μm) particle emissions have resulted in increasing requirements for improved perfromance of control devices in this particle range.

The electrostatic collection of aerosol particles is one of the leading and versatile air cleaning methods. It is suitable for efficient collection of both large and fine particles due to the significant electrical forces acting on the particle. This method is limited neither by resistance to the motion of the gas, as are scrubbers and filters, nor to large particles, as are gravitational systems and cyclones. Electrostatic precipitators have been utilised to clean air in industrial ventilation applications and smaller scale devices have been used for enhancing indoor air quality in offices, homes and public buildings such as clubs, schools, shops, etc.

The collection efficiency of an ESP is dependent on its electrical and mechanical design (applied voltage and current, size of collection cell, strength and distribution of the electric field) and the characteristics of both gas media (such as flow rate, temperature, moisture, the velocity distribution and turbulence level of the gas flow) and aerosol particles (size and charge, shape, electrical resistivity, density, *etc.*) (Durga-Prasad et al, 1995). It also depends on some physical non-ideal effects such as electric wind, baffles, re-entrainment, etc (Zhibin and Guoquan, 1994). Despite the fact that the theory of electrostatic precipitator technology has been extensively studied, most of the relationships used in ESP design have been empirical or semi-empirical. The design of ESPs today is generally based on previous experience with similar processes or on the results of pilot model precipitator studies (Parker K.R., 1997).

The performance of an ESP must be accurately assessed to ensure effective emission collection. Ways for determining the design parameters are those of mathematical modelling, experimental pilot-scale testing and full-scale testing. The use of models has not yet enjoyed

wide acceptance as the difference between the collection efficiencies predicted by the models and the measured values often exceeds the acceptable limits of error. The Deutsch-Anderson equation (Flagan and John, 1988) has traditionally been used as the basis for initial work on precipitator design. While it can be taken as a fractional efficiency equation, in practice it has been used for overall efficiency. Moreover, the Deutsch-Anderson equation, due to its simplifying assumptions of uniform flow, uniform particle drift, and infinitely high turbulent diffusitivity, does not describe the actual process. Over the last decades, a number of new, more sophisticated models, which are believed to be more accurate for estimation of the capture efficiency of electrostatic precipitators, have been developed. These were concerned with improvements in particle charging, particle collection, ion mobility, space charge interactions, electrical wave-form effects, back corona effects, and rapping re-entrainment. However, a lack of a comprehensive experimental database, especially in the submicrometer particle size range, makes it difficult to evaluate these models and their ability to predict precipitator performance under a range of application conditions.

The use of pilot-scale (laboratory) testing is by far the most common method to assess an ESP performance as it is very reliable and relatively inexpensive (Paulson, 1992). Although pilot scale tests are commonly used to predict performance for new applications, their results cannot be directly applied to full-scale plants without the use of scaling factors. Nevertheless, although full-scale (field) testing has been most desirable, it is often not practical (Paulson, 1992), thus pilot-scale tests have remained as the primary method to assist in ESP design.

Most of the work on evaluation of precipitator collection efficiency in the submicrometer particle size range has been concerned with one-stage ESPs. Only those of Hautanen et al. (1986), Research Triangle Institute (1993), Hanley et al (1994), Yoo et al (1996), and Zukeran et al (1997) were performed on two-stage pilot-scale ESPs in the size range of interest. However, none of them were conducted with environmental tobacco smoke, which is the

aerosol of particular interest for the present study. Hautanen et al. (1986) investigated the collection efficiency and ozone-production dependence of the ESP on charging current and collecting voltage in the particle size range of approximately 0.1-1.5 μm, *i.e*. has not covered ultra-fine particles. Furthermore, the nature of the test aerosol was not specified making it difficult to apply the data to the particular installations. The collection efficiency tests of Hanley et al (1994) were performed for KCl aerosol in the 0.01-3 μm particle size range and of Yoo et al (1996) for NaCl aerosol in the range of 0.03-0.2 μm. Both works showed that collection efficiency decreased with decreasing particle size for particles below about 0.03 μm. This phenomenon was attributed to charging limitations for small particles and was considered as a new non-ideal effect which cannot be explained by the Deutsh theory. The studies did, however, report a relative minimum in efficiency at approximately 0.1-0.2 μm diameter. Zukeran et al (1997) investigated a re-entrainment phenomenon under diesel flue gases.

This paper presents results obtained on the evaluation of collection efficiency of a two-stage pilot-scale ESP. The objectives of the investigation were to experimentally investigate the effect of particle size (with a focus on submicrometer particles) and of aerosol nature on precipitator efficiency over a range of collection velocities of the entire airstream. A special emphasis of the work was on evaluation of the ESP performance for environmental tobacco smoke (ETS). It is believed that the data presented can be used in compilation of a comprehensive experimental database that could be used in developing and/or evaluating the precipitator models and on which precipitator designers/manufacturers can base the design of new installations.

Basic Principles of Electrostatic Precipitation

The operation principle of electrostatic precipitators is based on two steps: charging the particles and subjecting them to a strong electric field, so that their electrical drift will cause them to deposit on the collecting walls.

Depending on the design of the precipitating section, ESPs fall into two categories: single-stage and two-stage precipitators. The single-stage precipitators consist typically of a corona wire and a plate electrode that serves as a collection surface. A high voltage between the wire and the collection surface generates a corona discharge, which produces a high concentration of unipolar ions. The ions cause effective particle charging and the electric field drives the charged particles to the collection surface.

Two-stage precipitators use separate ionising and collection sections. In the ionising section, dirty air particles pass between ionising wires and plates connected to a high voltage power supply. A high voltage potential ionises the air and charges particles as they pass through this highly ionised space. The charged particles then pass through the collector cell, where they encounter oppositely charged collector plates. The entire process occurs within a fraction of a second.

Particle capture in an electrostatic precipitator mainly depends on the way the particles are charged in the ionisation section, the flow, and electrodynamic conditions within the collecting channel. In a collector, the charged particles are transported to the collector surfaces by the combined influences of Coulomb’s force (due to electrostatic field) and of interactions with the flowing gas. In all industrial scale precipitators, the flow is turbulent and particle transport depends on the structure of the gas flow that consists of mean flow in the longitudinal direction and of fluctuating (turbulent) flow.

Experimental Methods

The collection efficiency tests were performed at Queensland University of Technology (QUT) facilities under controlled laboratory conditions. The experimental set-up consisted of a duct system, a system for supplying HEPA filtered air, an ESP, an aerosol generation system, an aerosol sampling and transport system, and a particle size distribution monitoring system.

Precipitator

The results presented in this study are based on performance assessment of two-stage electrostatic precipitator IONITRON, model PSA 1010, which represents a category of ESPs broadly used in Australia. The characteristics of the precipitator are presented in Table 1. The IONITRON precipitators are manufactured by Email Airhandling, Pty Ltd, Australia and installed as air cleaning devices mainly in commercial type buildings, such as offices, hospitals *etc*.

Test rig

The tests were performed at a filter test rig designed according to the AS 1324.2 - 1996 standard, which is based on the ASHRAE Standard 52.1 – 1992. A schematic diagram of the rig is shown in Figure 1. The main parts of the system are duct, filter-accommodating section, fan and the fan control unit, inlet and outlet HEPA filters. The system allows testing of filters under three different modes: draw-through (negative pressure), blow-through (positive pressure) and recirculating. This is achieved through different configuration of a set of adjustable air dampers controlling the path of the flow. In this study the filters were tested under the draw-through mode. Complete mixing of challenge aerosols within the entire

airstream was achieved using two mixing baffle plates installed inside the rig. The location of the plates and sampling points upstream and downstream was according to the AS 1324.2-1996, fulfilling the criteria for perfect mixing. Aerosols were sampled by two identical isokinetic probes, connected to the instruments by conductive silicone tubing of the same length.

Test aerosols

Two types of test aerosols were used to evaluate the removal efficiency of the precipitator in the submicrometer range: NaCl and ETS. The ETS was an aerosol of particular interest for the present project and the method of its generation is described below. The NaCl aerosol was selected as the alternative challenge aerosol for preliminary tests. It was assumed that the results obtained by using NaCl aerosol would give considerable information about the properties of the precipitator when exposed to various test aerosols, including ETS.

The polydisperse NaCl test aerosol was generated by nebulising 10% and 20% aqueous NaCl solutions using a Collison nebuliser. Following generation, the aerosol was passed through a charge neutraliser to eliminate any electrostatic charge on the particles.

Aerosol sampling

The sampling probes were constructed in accordance with isokinetic sampling requirements. Upstream and downstream sampling lines were identical (made of the same material and the same length) to minimise measurement error associated with particle losses during aerosol sampling due to gravitational settling and inertial losses in bends.

Instrumentation

The experimental instrumentation used in the present tests included an Environmental Tobacco Smoke (ETS) generator, Collision nebuliser, a charge neutraliser, a Scanning Mobility Particle Sizer (SMPS), and an Aerodynamic Particle Sizer (APS).

The ETS generator was designed at the Environmental Aerosol Laboratory of QUT and manufactured by Email Airhandling for the purpose of these studies. It allows simultaneous smouldering of up to twenty cigarettes and introduction of the generated ETS into the test rig. The generator consists of a metal/perspex box, cigarette holder, electrical ignition system, a small air fan, and sampling and delivery probes.

After cigarettes were ignited by an electrically heated filament, the process of smouldering continued due to air movements inside the box, caused by the fan. The generated smoke was drawn into the test rig by the pressure difference existing between the test rig and the ETS generator.

A Collision nebuliser was used to generate the NaCl test aerosol. It provides a reliable, stable and repeatable method for generation of aerosols of a required particle size range at high concentration levels (up to 10^7 particles.cm^{-3}). The aerosol size range is controlled by varying the concentration of solute in the nebulised solution.

A charge neutraliser *(TSI Model 3012)* was used to eliminate the effect of static charging of the aerosol generated by the Collision nebuliser. It consists of two embedded, hollow cylinders with a small amount of radioactive ^{85}Kr gas sealed within their walls. The test aerosol was brought to Boltzman electrical equilibrium by exposing it to a cloud of bipolar ions produced by the radioactive source while passing through the neutraliser.

Particle measurement instruments

The APS and the SMPS were used to measure particle size distributions and concentrations. The SMPS was used to measure particle number concentrations in the size range of 0.018-0.7 μm and the APS for measurements of particles in the range of 0.5-1.2 μm.

Scanning Mobility Particle Sizer (SMPS) TSI Model 3934 consists of an Electrostatic Classifier and Condensation Nucleus Counter (CNC).

The nominal size range covered by this instrument is from 0.005 to 1 μm. The SMPS uses a bipolar charger in the electrostatic classifier to charge particles to a known charge distribution. The particles are classified according to their ability to traverse an electrical field, and counted with a CNC. The Condensation Nucleus Counter (in this case TSI Model 3025A) can be used as a part of the SMPS or individually as a particle counter. The CNC uses a vapour sheath technique to improve the instrument's lower particle size sensitivity. The particles are detected and counted by a simple optical detector after a supersaturated vapour condenses onto their surfaces, causing them to grow into larger droplets.

The SMPS measures particle concentrations in the range from 20 to 10^7 particles.cm^{-3} with a minimum sampling time of one minute. The window size applied during a scan depends on the selection of the impactor, the total sampling time, and the values of the sample and sheath air flow rates.

Aerodynamic Particle Sizer (TSI Model 3320) is a particle spectrometer that measures both aerodynamic diameter and light-scattering intensity. It provides a count size distribution for particles with aerodynamic diameters from 0.5 to 20 μm in real time. The instrument operates on the principle that particles of different sizes, after being accelerated in a flow field, achieve

different velocities. A laser scan technique allows measurement of these velocities, which are later used for calculation of particle diameter.

Test procedure

Although the blow-through mode appears to be a more appropriate operating method (in order to minimise the possibility of infiltration of room aerosol due to air leakage into the test rig), the tests were mainly performed under the draw-through mode. This was caused by the difficulties experienced with injecting of the ETS aerosol into the duct under the blow-through mode. For comparative purposes, in order to assess the effect of the type of test aerosol on the collection efficiency, the tests with the NaCl aerosol were also performed mainly under the draw-through mode. Only a few preliminary tests were carried out under blow-through mode using the NaCl aerosol in order to assess the effect of the type of system mode on the collection efficiency. The precipitator was tested at volumetric flow rates of 472, 560, 708, 800, 944, 1024, and 1050 $L.s^{-1}$.

For each set of conditions, a series of three upstream and downstream background concentrations were measured first. The aerosol generator was then turned on, allowed to stabilise for 5-10 minutes, and a series of upstream and downstream measurements were performed without precipitator in the system (P_{100}, 100% penetration tests). The purpose of the P_{100} tests was to evaluate the adequacy of the overall duct, sampling, and measurement systems.

After the P_{100} measurements were concluded, the precipitator was activated and particle size fractional efficiency tests were carried out. In case of the ETS aerosol, the measurement procedure included three sequential measurement pairs of upstream and downstream sample concentrations to obtain the challenge and penetrating aerosol concentrations, respectively. The average of these results was used to calculate the removal efficiency. The sequential

sampling regime was selected in order to minimise the effect of the ETS generator variability. In case of the NaCl aerosols, since the Collison nebuliser was capable to generate stable aerosol concentrations over entire experiment, three simultaneous upstream measurements were followed by three simultaneous downstream measurements (using either the SMPS or the APS, depending on particles size range). Each measurement was taken over a time period of two minutes.

The p*enetrations* P, both total and corresponding to the different particle size channels $d_{p,i}$ of the particle size analyser, were calculated as:

$$P = P_{meas}/P_{100} \quad (1)$$

where:

$$P_{meas} = (D_{avr} - D_{bkg})/ (U_{avr} - U_{bkg}) \quad (2)$$

$$P_{100} = (D_{avr\text{-}100} - D_{bkg\text{-}100})/ (U_{avr\text{-}100} - U_{bkg\text{-}100}) \quad (3)$$

where:

D_{avr}, U_{avr} - averaged downstream and upstream aerosol concentrations, respectively (challenge aerosol generator on, precipitator on);

D_{bkg}, U_{bkg} - averaged background downstream and upstream aerosol (challenge aerosol generator off, precipitator on).

$D_{avr\text{-}100}$, $U_{avr\text{-}100}$ - averaged downstream and upstream aerosol concentrations during P_{100} test, respectively (challenge aerosol generator on, precipitator off);

$D_{bkg\text{-}100}$, $U_{bkg\text{-}100}$ - averaged background downstream and upstream aerosol concentrations during P_{100} test, respectively (challenge aerosol generator off, precipitator off).

The corresponding removal e*fficiencies* were calculated as:

$$Eff = (1 - P) \times 100\% \qquad (4)$$

Results and Discussion

Comprehensive work was carried out in order to evaluate the effect of the flow rate on the fractional collection efficiency using the NaCl test aerosol. Several tests were performed to assess this relationship for the ETS challenge aerosol.

P_{100} test

For an ideal system, a measured penetration value of one for all particle sizes should be obtained. Deviation from one can occur due to particle losses in the duct, differences in the degree of aerosol uniformity at the upstream and downstream probes, and differences in particle transport efficiency in the upstream and downstream sample lines. In the present tests, P_{100} values were found to be within 0.90 - 0.99 over the entire size range. These were used to calculate the penetration values in accordance with the equation (1).

Tests with the NaCl challenge aerosol

The results of the collection efficiency tests performed using the NaCl test aerosol are shown in Figures 2-8. Figures 2 and 3 represent the particle size distribution of upstream and downstream aerosol generated from 10% solution at two extreme flow rate values: 1050 and 472 $L.s^{-1}$, respectively. The spectra were unimodal with a count median diameter (CMD) of about 0.17 μm with the geometric standard deviations (GSD) typically within 1.5 –1.7. These

results were obtained with the SMPS. The APS spectra (Figures 4-5) of the aerosol generated from 20% NaCl solution had a CMD of about 0.7 μm with GSP of 1.6-1.8.

The fractional efficiencies data from the first series of tests, for the aerosol with CMD of 0.17 μm (which were obtained with the SMPS), are plotted on a graph shown in Figure 6. The data are presented for seven flow rates ranging from 472 to 1050 $L.s^{-1}$. As can be seen, the fractional collection efficiency (further referred to as efficiency) of the precipitator dramatically increases with a decrease of the flow rate. The experimental data have also demonstrated that efficiency is significantly dependent on the particle size. However, this dependence reduces with a decrease in the flow rate to such an extent that it becomes independent of the particle size. For example, at flow rates of 472 $L.s^{-1}$, the efficiency was found to be almost independent of particle size, within the limits of the experimental error (about 5%). At flow rates above 560 $L.s^{-1}$, the data reveal that a gradual increase of particle size results in:

- an increase in removal efficiency of small particles, for those up to about 0.035 μm;
- a decrease in the removal efficiency of particles over the range from about 0.035 μm to about 0.1 μm;
- an independence of collection efficiency on particle size for particles over the range from about 0.1 μm to about 0.45 μm;
- an increase in the collection efficiency for particles larger than about 0.45 μm.

Summarising the results of the tests performed at flow rates greater than 560 $L.s^{-1}$, the following conclusions can be made. For submicrometer particles, the highest collection efficiencies are achieved over the range of approximately 0.025 to 0.04 μm. For example, a maximum collection efficiency of 89.0% was detected for particles of 0.34 μm at a rated flow

rate of 944 $L.s^{-1}$. This finding does not agree with the data of Hanley et. al. (1994) and Yoo et. al. (1996) who reported a decrease of the efficiency for particles below about 0.03 μm.

The lowest collection efficiencies are achieved for particles smaller than about 0.02 μm. To illustrate, the efficiency of 45.1% was detected for 0.022 μm particles at a flow rate of 944 $L.s^{-1}$. Relatively low but steady efficiencies were measured over the range of approximately 0.1 to 0.5 μm. Ignoring the data obtained for particles below 0.025μm, this range could be considered as the one where minimum collection efficiencies were observed. For comparison, at a flow rate of 944 $L.s^{-1}$ the efficiency of about 70 % was measured over the range of 0.19-0.52 μm.

These results can be explained by the collection mechanism and operation principle of the electrostatic precipitators. The lower efficiency of extremely small particles (less than 0.02 μm) can be attributed to the charging limitations of the particles, and the lower efficiency of larger particles can be attributed to their mobility limitations. An increase in the diameter of a charged particle corresponds to a decrease in its electrical mobility. Thus particles with larger diameters will travel shorter distances over the same time period, than smaller diameter particles, when under the influence of an electric field. For a high flow rate through an electrostatic precipitator, some larger particles may not have enough time (due to their small electrical mobility) to traverse the field and deposit onto the precipitator plates. In this case, the collection efficiency of the precipitator for this particle size is very low. There is no sharp cut-off point for the efficiency however, as all particles do not carry the same charge, and they do not enter the precipitator at the same distance from the plates. Particles with a higher charge can have the same mobility as smaller particles with a lower charge, and can thus be collected. Particles entering close to the precipitator plates will require less time to be collected than particles entering mid-way between the plates.

The fractional efficiency data from the second series of tests (which were obtained with the APS), for the aerosol with CMD of 0.7 μm, are given in Figure 7. It can be seen from this Figure that the results obtained with both instruments (APS and SMPS) are consistent. The general trend of the precipitator performance observed in that particle size range is that the collection efficiency increases with an increase of particle size. The effect of the flow rate on the collection efficiency however appears to decrease with an increase of particle size. The important observation is that for the particles of an aerodynamic diameter of 1.2 μm the collection efficiency becomes almost independent of the flow rate. However, those data can be considered rather as preliminary due to low counts for particle diameters greater than 1 μm. Further work is required to make the final conclusions on the ETS performance trends for particle diameters above 1 μm.

The results of the total collection efficiency tests are presented in Figure 8, where the effect of flow rate on the total collection efficiency for the two cases investigated (for the NaCl aerosol with CMD of 0.17 and 0.7 μm) is demonstrated. Two trends were observed: (1) total efficiency is increased with the increase of particle size. For example, at flow rate of 944 $L.s^{-1}$, the total collection efficiency values of 75.2% and 80.4% were found to correspond to the aerosols with CMD of 0.17 and 0.7 μm, respectively; (2) there is a second-degree polynomial dependency of the total collection efficiency on the flow rate. In case of the aerosol with CMD=0.17μm, such a dependency is described by the equation:

$$y = -2E\text{-}05x^2 - 0.0154x + 107.95, \quad (5)$$

with a correlation factor (R^2) of 0.9994.

In case of the aerosol with CMD=0.7 μm, it is described as follows:

$$y = -4E\text{-}05x^2 + 0.0252x + 93.858, \quad (6)$$

with $R^2 = 0.9955$.

Tests with the ETS challenge aerosol

The tests were carried out under the draw-through mode with volumetric flow rates of 472 and 944 $L.s^{-1}$. Results of these tests are presented in Figures 8-10. Figures 8 and 9 are the spectra of upstream and downstream aerosol size distributions that are based on the SMPSs measurements. The spectra are unimodal with a CMD of about 0.13-0.14 μm with a GSD of 1.6 –1.7. The corresponding effect of flow rate on the fractional collection efficiency is shown in Figure 10. It can be seen that the fractional efficiency results of tests with ETS have showed a similar pattern to tests with the NaCl aerosol. Total collection efficiency values of 71.8 and 95.2 % were found for flow rates of 944 and 472 $L.s^{-1}$, respectively. These values are very close, within limits of experimental error, to that obtained for the NaCl aerosol with CMD=0.17 μm. In other words, for the cases investigated, the IONITRON electrostatic precipitator has demonstrated similar performance for the NaCl and the ETS aerosols. These data confirm results obtained earlier by Jamriska et al (1998). It indicates that despite the fact that these two aerosols have different origin (ETS is a combustion aerosol and NaCl is an atomised one), shape, and chemical and physical-chemical properties, they demonstrate similar behaviour during electrostatic precipitation. This finding is important since aerosol nature (particle characteristics) is one of the main parameters thought to affect the performance of the ESP which should be considered by engineers designing or comparing precipitators (Cheremisinoff and Young, 1977).

Conclusions

An experimental study on the performance of the commercially available two-stage electrostatic precipitator has been conducted for fine particles of two origins, NaCl and ETS. The tests covered the particle size range from 0.018 -1.2 μm and were performed over a range of flow rates. Overall conclusions from the study can be summarised as follows:

1. For the cases evaluated, the total collection efficiency of the IONITRON electrostatic precipitator was found to have no dependence on the type of test aerosol. The total collection efficiency values of 72 ± 8 % and 75 ± 5 %, measured at flow rate of 944 $L.s^{-1}$, were found to correspond to the ETS (CMD=0.14 μm) and the NaCl (CMD=0.17 μm) test aerosols, respectively. Thus, the data of the present work demonstrate that for future studies the NaCl aerosol is an appropriate substitute for the ETS aerosol.
2. The total efficiency was found to increase with the increase of count median diameter of the particles.
3. There is a second-degree polynomial dependency of the total collection efficiency on the flow rate.
4. The fractional efficiency of the electrostatic precipitator was found to be dependent on flow rate. However, the “critical” particle size of about 1.2 μm was found to exist when the collection efficiency becomes independent of face velocity.
5. For particles smaller than 1 μm, the fractional collection efficiency was found to be independent of particle size at flow rates below 560 $L.s^{-1}$. At higher flow rates, however, a significant dependency of the efficiency on particle size was observed. A relative minimum in the efficiency was observed for particles smaller than about 0.02 μm and over the range of 0.1 to 0.5 μm. This phenomenon is attributed to the charging limitations

of the particles as well as the strong diffusion component in the drift velocities, and that of larger particles is attributed to their mobility limitations.

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Table 1

Parameter	Symbol	Unit	Value
Width of charging cell	W_1	mm	110.0
Length of charging cell	L_1	mm	535.0
Radius of wire	R_w	mm	0.075
Height of collecting plate	W_2	mm	301.5
Length of collecting plate	L_2	mm	562.0
Voltage of corona wire	V_1	kV	13.0
Voltage of plate	V_2	kV	6.5
Number of plates	N_p	-	61
Distance between plates	D_p	mm	7.0
Flow rate through precipitator	U	L/sec	472-1050
Gas temperature	T	^oC	30-32

Fig. 1

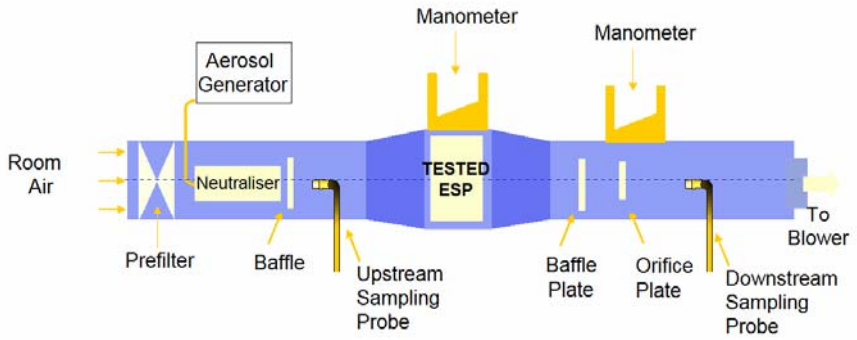

Fig.2

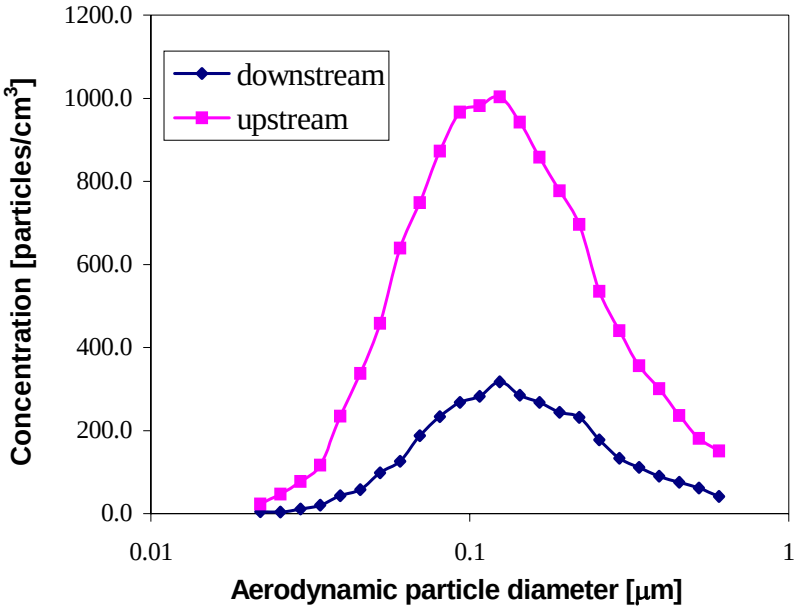

Fig.3

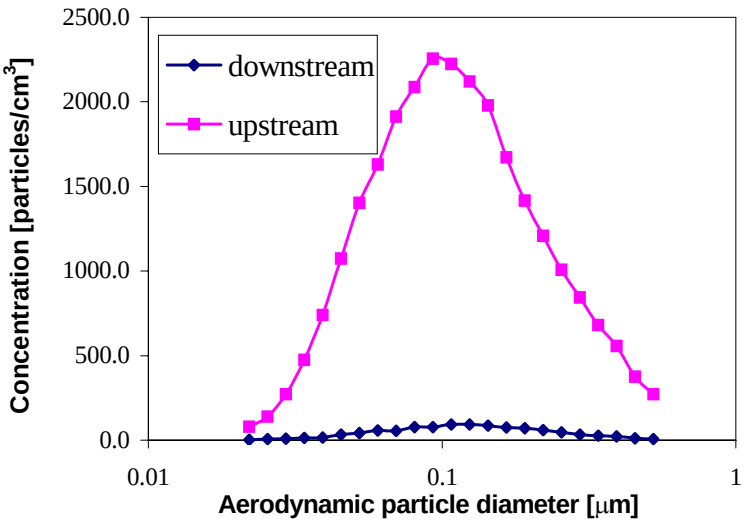

Fig.4

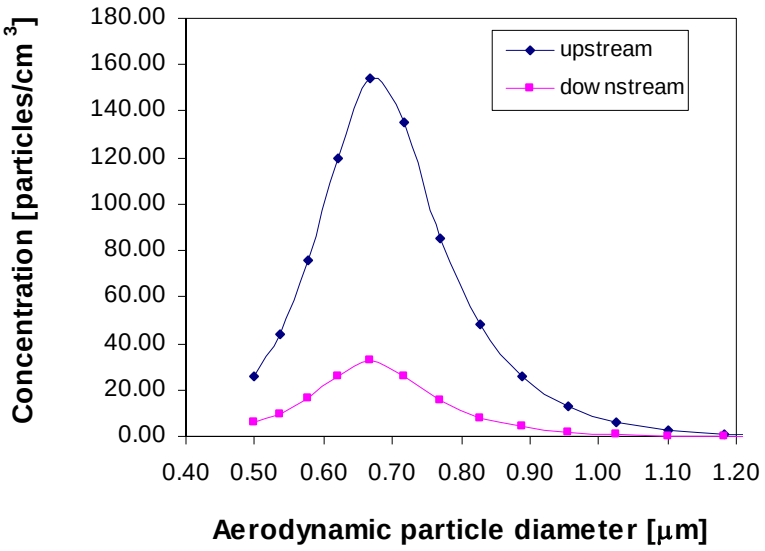
Concentration [particles/cm 3]
180.00
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20
Aerodynamic particle diameter [µm]
upstream
downstream

Fig.5

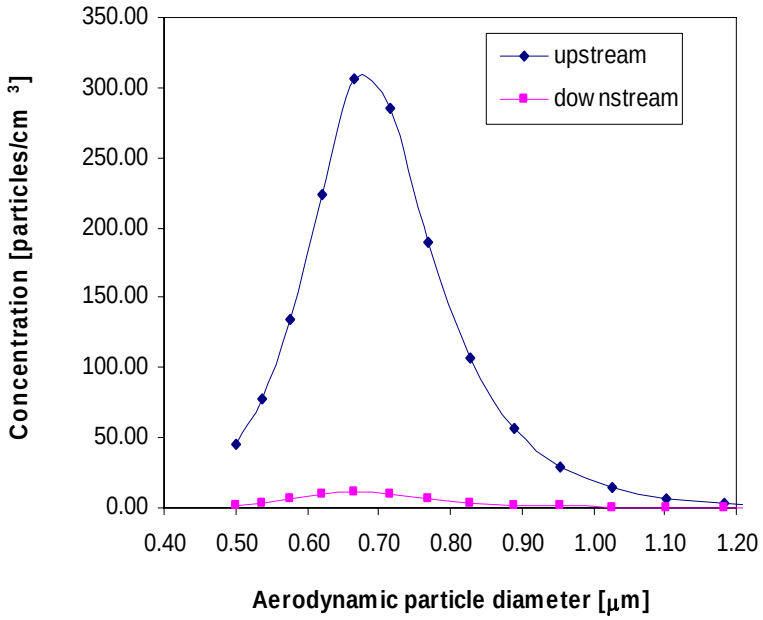
Concentration [particles/cm 3]
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20
Aerodynamic particle diameter [µm]
upstream
downstream

Fig.6

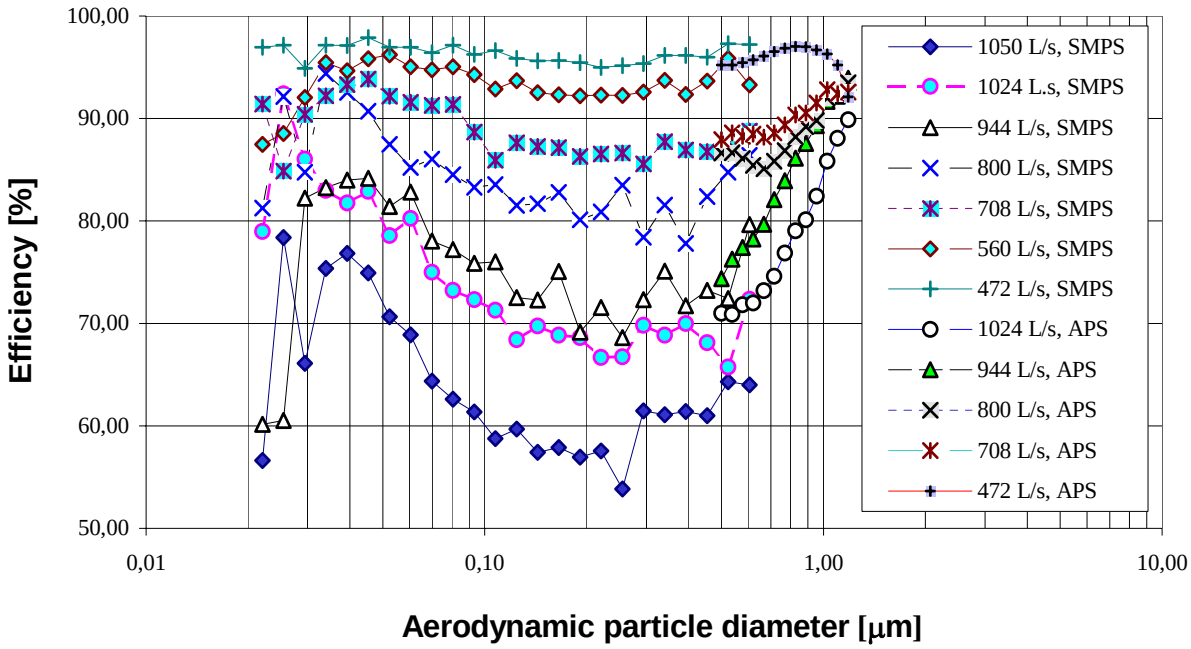
100,00
90,00
80,00
70,00
60,00
50,00
Efficiency [%]
0,01
0,10
1,00
10,00
Aerodynamic particle diameter [μm]
1050 L/s, SMPS
1024 L.s, SMPS
944 L/s, SMPS
800 L/s, SMPS
708 L/s, SMPS
560 L/s, SMPS
472 L/s, SMPS
1024 L/s, APS
944 L/s, APS
800 L/s, APS
708 L/s, APS
472 L/s, APS

Fig.7

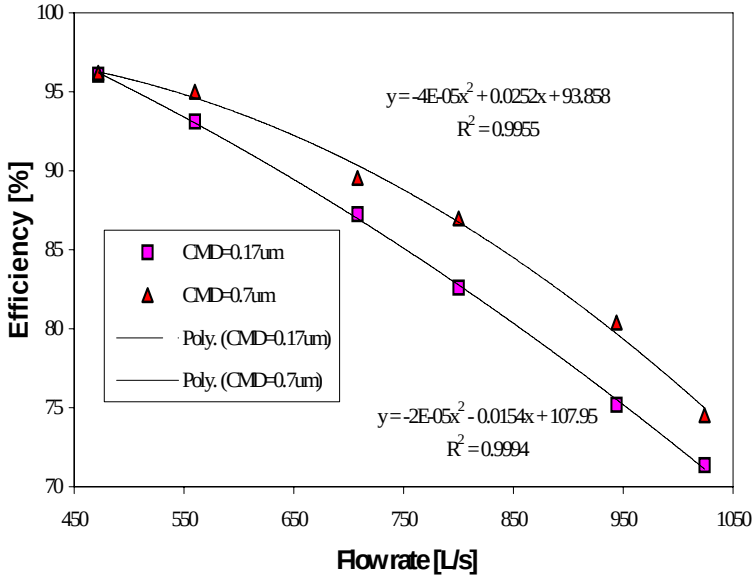
100
95
90
85
80
75
70
Efficiency [%]
450
550
650
750
850
950
1050
Flowrate [L/s]
y = -4E-05x2 + 0.0252x + 93.858
R2 = 0.9955
y = -2E-05x2 - 0.0154x + 107.95
R2 = 0.9994
CMD=0.17um
CMD=0.7um
Poly. (CMD=0.17um)
Poly. (CMD=0.7um)

Fig.8

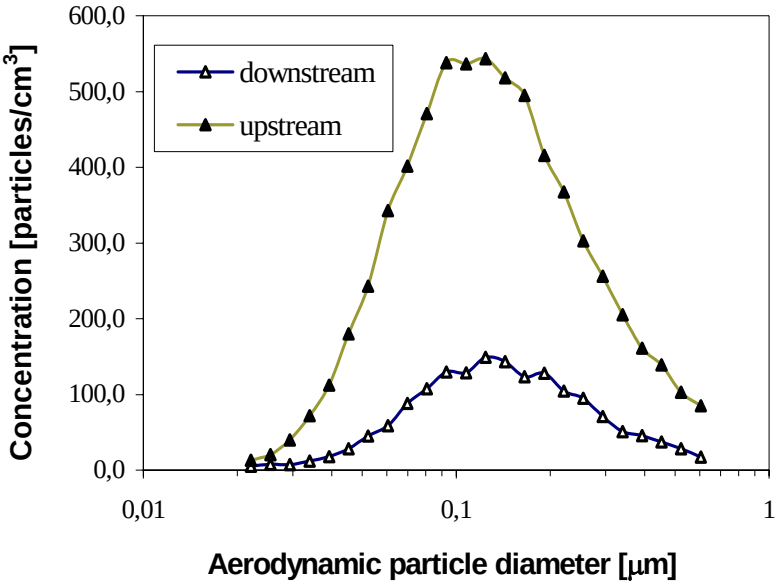

Fig.9

Fig.10