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High collection efficiency electrostatic precipitator for in vitro cell exposure to concentrated ambient particulate matter (PM)

Markus Sillanpää, Michael D. Geller, Harish C. Phuleria, Constantinos Sioutas*

Department of Civil and Environmental Engineering, University of Southern California, 3620 South Vermont Avenue, Los Angeles, CA 90089, USA

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Abstract

A new sampling system, the in vitro electrostatic collector, was developed to collect ambient particles for in vitro studies. The system consists of two units: first, particles are concentrated by means of the versatile aerosol concentration enrichment system (VACES), and subsequently they are drawn through an electrostatic precipitator (ESP). The particle sample is collected on a petri dish that contains cell cultures, or on any other desirable substrate suitable for particle collection and analysis. The VACES makes it possible to sample for short time intervals, which favors cell viability and exposure characterization. The laboratory tests showed that collection efficiency under optimized conditions is higher than 95% across all particle diameters measured (18 nm to 3.0 μm), regardless of aerosol type. The field experiments showed that the VACES with a tandem-virtual impactor system is capable of concentrating ambient ultrafine, accumulation and coarse particles by 80–100 times. The in vitro electrostatic collector has the potential to perform hourly direct, solvent-free PM collections for toxicological studies.

Keywords: Aerosol sampling; High efficiency; Electrostatic precipitator; Particle concentrator; In vitro exposure; Ultrafine particles

1. Introduction

Urban air particulate matter (PM) is a highly complex mixture of different-sized solid and liquid particles orginating from a large variety of anthropogenic and natural sources. Epidemiological studies have most often given stronger exposure–response relationships for mortality and morbidity outcomes in association with fine particles ($PM_{2.5}$; $D_p < 2.5$ μm) than with PM_{10} ($D_p < 10$ μm) (USEPA, 2004; WHO, 2003). However, in a recent meta-analysis, coarse particles ($PM_{10-2.5}$; 2.5 μm $< D_p <$ 10 μm) have been associated more strongly than $PM_{2.5}$ with respiratory hospital admissions (Brunekreef & Forsberg, 2005). Ultrafine particles ($PM_{0.1}$; $D_p < 0.1$ μm) have been the most recent focus of research because they are thought to pose a great risk to human health due to their high number concentration in urban environments and ability to penetrate deep into the alveolar region of the lung and, in turn, into the bloodstream (Delfino, Sioutas, & Malik, 2005). Recent toxicological studies suggest that ultrafine particles may elicit a higher adverse response per unit mass than fine and coarse particles (Donaldson, Stone, Clouter, Renwick, & MacNee, 2001; Li et al., 2003; Oberdörster, 2001; Xia et al., 2004).

* Corresponding author. Tel.: +1 213 740 6134; fax: +1 213 744 1426.
E-mail address: sioutas@usc.edu (C. Sioutas).

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The fluctuation of important atmospheric parameters, which influence ambient PM concentrations (hence human exposure), may take place in time scales that are substantially less than a few hours. These include emission strengths of particle sources, temperature, relative humidity and mixing height as well as wind direction and speed. Ideally, ambient PM should be collected using direct and on-line methods so that measurement of its chemical and toxicological properties, including oxidative potential, can be conducted on the unaltered particles. However, on-line measurements of many PM properties (e.g., chemical composition, endotoxin, oxidative potential) are not currently available, and therefore PM must first be collected on filters, or in liquid suspensions before it can be assayed.

Traditionally, ambient particles have been collected for toxicological analysis by using filter samplers in conjunction with preselective PM inlets. Particles collected on a filter must be removed (often via solvent extraction) prior to in vitro instillation. Despite its simplicity and widespread use for PM sampling, filtration suffers from several shortcomings with regard to the sample pretreatment (e.g., extraction, lyophilization of solvent and sonication) and artifacts during sampling, i.e., evaporation of semi-volatile compounds, adsorption of gases on the filter material and reactions between collected particles and gaseous compounds (Eatough et al., 1999; Turpin, Saxena, & Andrews, 2000). In addition, Dick et al. (2000) showed that components of filters used to collect particles could contaminate the extract preparation and interfere with biological investigations. As an alternative sampling method, impaction has been applied for PM collection for in vitro toxicity studies (Chang, Sioutas, & Cassee, 2001). This method has the advantage of a much smaller collection surface area over filtration, which in turn makes extraction easier, as particles are collected on top of a flat surface, and not inside the fibers/mesh of a filter. Additionally, gas adsorption in impactor sampling plays a less significant role because the air does not pass through the collection substrate (as in filtration). Nevertheless, the impactor sample also suffers from the difficulties due to sample preparation. Ultimately, any extraction process in which particles are removed from a collection substrate with a solvent may not preserve the original physical characteristics of the particles. Once in a liquid extract, the particles may experience physical and chemical changes (e.g., soluble components will be leached off the particulate phase) and coagulation, all of which could significantly affect particle surface area and number—two properties thought to be influential in toxicological response. Additionally, the lower cutpoint of most conventional impactors, certainly those operating with high flow rates that are required to collect sufficient amounts of PM in relatively short periods, is of the order of 0.1–0.2 μm (Misra, Fine, Singh, & Sioutas, 2004), which means that the ultrafine PM fraction still needs to be collected by means of filtration with all of its disadvantages explained above.

The development of ambient particle concentrators (e.g., Gordon, Gerber, Fang, & Chen, 1999; Kim, Sioutas, & Chang, 2000; Sioutas, Koutrakis, Ferguson, & Burton, 1995; Sioutas et al., 1997) has enabled researchers to investigate exposures to ambient aerosols at increased concentrations, and thus shorter sampling intervals, and to collect a large amount of PM material in aqueous suspension suitable for subsequent toxicological assays. Results indicate that concentrated ambient aerosol exposure systems may be a useful method for assessing health effects associated with ambient particles (e.g., Godleski, Sioutas, Katler, & Koutrakis, 1996; Gong, Jr., et al., 2000). Kim, Jaques, Chang, Froines, and Sioutas (2001) developed a versatile aerosol concentration enrichment system (VACES) that uses a super-saturation/condensation system to rapidly enlarge particles to super-micrometer droplets, which are concentrated by means of a dichotomous virtual impactor (VI). This system is useful as a semi-portable unit to concentrate particles of coarse, fine and/or ultrafine PM. Highly concentrated liquid suspensions of these size-fractionated aerosols are obtained by connecting the concentrated output flow from each concentrator to a liquid impinger (BioSampler^{TM}, SKC West Inc., Fullerton, CA, USA). Even though this method does not require filter pretreatment and is not affected by filter sampling artifacts, it is also an indirect procedure and thus may not best simulate the real exposure of human cells to ambient air particles.

An interesting approach for the measurement of ambient bioaerosols applies a flat-plate electrostatic precipitator (ESP) that was designed and developed by Mainelis, Willeke, Adhikari, Reponen, and Grinshpun (2002). In this sampler, two commercial ionizers charge the incoming particles, which are then subjected to a precipitating electric field and are collected onto small square agar plates positioned along the flow axis. Due to the low particle velocity toward the collection medium, the ESP offers the potential of a "gentle" particle collection method, unlike impactors and impingers, whose high collection velocity may cause damage to microorganisms. A similar configuration may allow direct collection of particles onto cell cultures for in vitro testing of their redox properties. Because sampling air flows over the cell cultures at quasi-ambient relative humidity, collection time of this method has to be limited to at most 1–2 h in order to not compromise the cell viability. Furthermore, ESPs developed for these purposes suffer from low collection efficiencies, especially for ultrafine particles.

The main objective of this study is to develop a new electrostatic collector of ambient particles, including the sub-100 nm fraction, for in vitro collection directly onto a cell culture. The electrostatic collector for in vitro studies combines two technologies—an aerosol concentrator and an ESP. The performance of a newly designed ESP has been tested with different types of mono- and polydisperse laboratory aerosols as well as with indoor air particles. For the field collections of ambient particles, the ESP was preceded by a VACES, employing a tandem-VI system, which has been evaluated first in the laboratory and then in the field by using a number of different aerosol monitors.

2. Experimental methods

2.1. Design of the in vitro ESP collector

The in vitro electrostatic collector is a tandem of two technologies: (1) the VACES, and (2) a newly developed ESP. The schematic of the in vitro electrostatic collector is shown in Fig. 1. The two major components of the system are described below.

2.1.1. Particle concentrator

The VACES is a patented particle concentrator that is described in detail in Kim, Jaques, Chang, Froines, et al. (2001) and Kim, Jaques, Chang, Barone, et al. (2001). Sampling air is drawn over a pool of warm distilled water to achieve saturation, and subsequently, it passes through a cooling condenser that allows the fine/ultrafine particles to grow to super-micrometer ($\sim 3\,\mu m$) size. The cutoff size of ultrafine or fine particles can be obtained by placing the proper impactor inlet in front of the saturator. In order to increase particle concentration, the grown particles are then drawn through a VI. The specific VACES system used in conjunction with the ESP employs two VIs in parallel, concentrating particles first from a total flow of 200 l/min to a flow of 15 l/min. The concentrated particle stream from the combined minor flows of two VIs then passes through a second VI that concentrates particles from 15 to 1.8 l/min. The overall concentration factor for the tandem concentrator is ideally 110 times (200 l/min down to 1.8 l/min). Both of the above-mentioned impactors have a 50% cutoff size of about 1.5 μm at their respective nominal flow rates. The concentrated particles from the minor flow of the second-stage VI are drawn through a diffusion dryer that removes the excess water and returns the particles to their original sizes. For the collection of larger particles than 1.5 μm, the concentrator is used with the VIs only, and without the pre-impactor, saturator, condenser and diffusion dryer.

2.1.2. Electrostatic precipitator

The concentrated particles pass through the ESP at 1.8 l/min. The internal dimensions of the insulated ESP are 10 cm in diameter and 4.5 cm in height. Circular aluminum plates cover the internal upper and lower surfaces. Conductive adhesive is used to affix two 10 mm long nickel tacks to the upper aluminum plate, which are used to generate the positive corona. The tacks are placed along the sampling flow in the distance of 2 cm from each other. A high voltage power supply (Model Bertran Series 915, Spellman High Voltage Electronics Corp., Hauppauge, NY, USA) was used to generate voltage to the ESP. The upper aluminum plate is connected to the precipitation voltage (V_{ESP}) while the lower plate is grounded. The strength of ESP electric field (E_{ESP}) was calculated by dividing an applied V_{ESP} (kV) by the distance ($H = 3.4$ cm) from the tip of corona needles to the ground electrode. The sampling flow enters and exits (opposite side) about 1 cm beneath the top electrode. The inlet and outlet of the ESP can be altered based on the needs of the specific study. The ESP housing is constructed from standard polyvinyl chloride (PVC) pipe fittings due to its electrical insulating capacity. The top and bottom can be easily disassembled for maintenance or exchange of cell culture plate/filter.

2.2. Test particles and instrumentation

The ESP and VACES were tested separately and the measurements were done alternately in the upstream and downstream of the system. The ESP was tested in lab experiments using different types of aerosols. Then, the VACES was deployed in the field for testing with ambient urban PM in conjunction with continuous and time-integrated monitors, as discussed in the following paragraphs. All these laboratory and field measurements have been repeated at least three times.

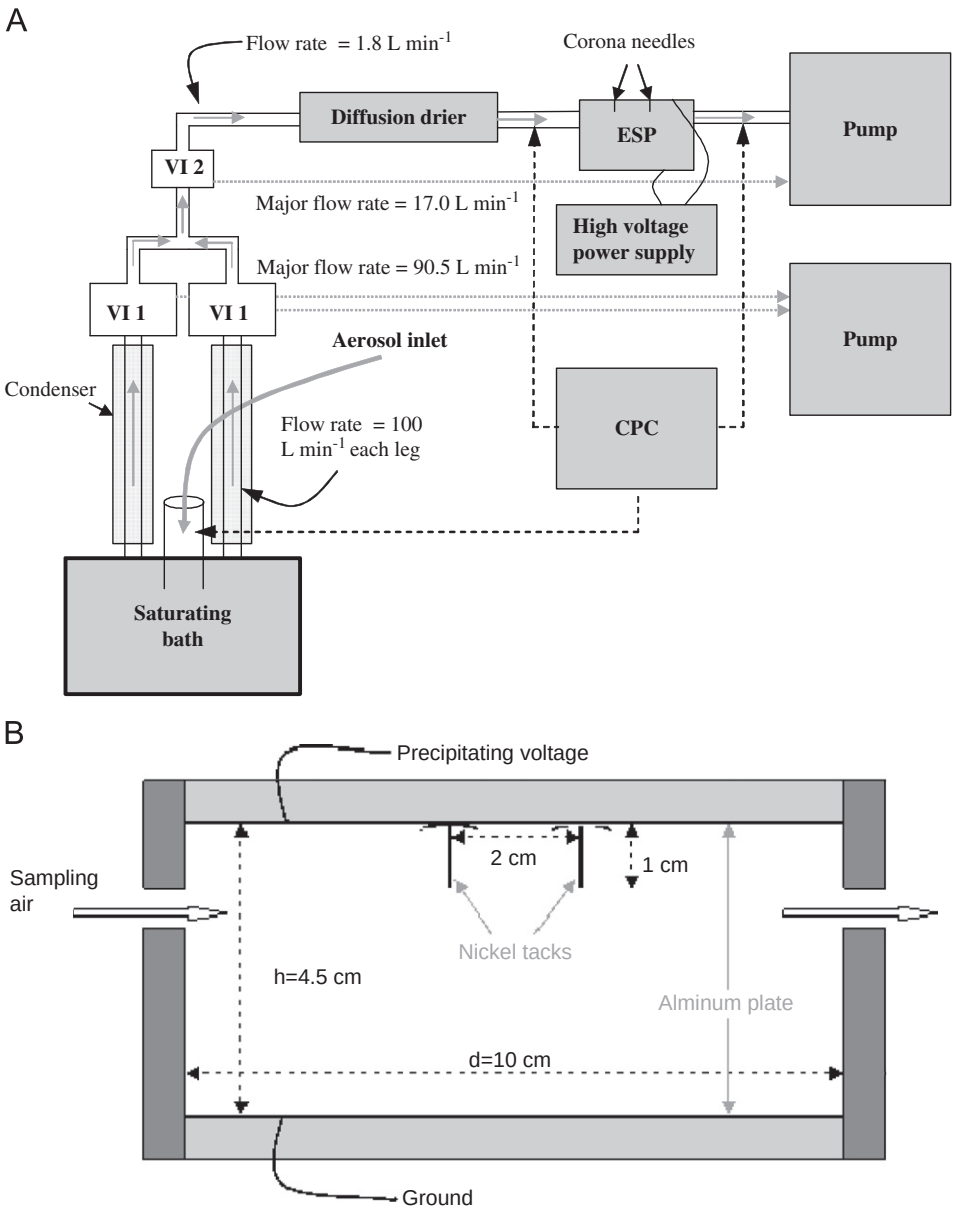

Fig. 1. (A) Schematic diagram of the in vitro electrostatic collector and (B) cross-sectional view of the cylindrical flat-plate ESP.

The performance of the ESP was tested with monodisperse polystyrene latex (PSL) particles (Polyscience Inc., Warrington, PA, USA) of various sizes as well as polydisperse ammonium sulfate and glutaric acid particles. The particles were aerosolized with a nebulizer (VORTRAN Medical Technology Inc., Sacramento, CA, USA). Due to monodispersity, the PSL particles were selected to demonstrate the preservation of physical aerosol properties during the collection process. These particles have also high electrical resistivity and thus represent a worst-case scenario for electrostatic collection. Ammonium sulfate was selected as a test aerosol because of its high contribution to ambient $PM_{2.5}$ mass (Malm, Schichtel, Pitchford, Ashbaugh, & Eldred, 2004). Glutaric acid is a dicarboxylic acid found in ambient aerosols and was chosen to represent a typical product of secondary aerosol formation by photo-oxidation of organic gaseous precursors (Cruz & Pandis, 1999).

The instruments used in this study are shown in Table 1. A scanning mobility particle spectrometer (SMPS; Model 3936, TSI Inc., Shoreview, MN, USA) and aerosol particle sizer (APS; Model 3321, TSI Inc., Shoreview, MN, USA)

Table 1
Instrumentation and parameters investigated

Instrument	Parameter	Flow rate (l/min)	Target of use
Aethalometer[a]	Black carbon	2.0	VACES
APS[b]	Particle size distribution (0.542–19.81 μm)	5.0	ESP, VACES
CPC[c]	Total number concentration	0.3/1.4	ESP, VACES
DataRAM 2000[d]	PM mass	2.0	VACES
UV Spectrometer[e]	Fluorescence	–	ESP
NSAM[f]	Nanoparticle surface area	2.5	VACES
Ozone Monitor[g]	Ozone concentration	2.0	ESP
PAS[h]	Particle-bound PAHs	1.0 + 1.0	VACES
SMPS[i]	Particle size distribution (15.7–638 nm)	0.3/1.4	ESP, VACES

[a]Two-channel (BC + UV) (Model AE-21, Thermo Andersen, Smyrna, GA, USA).
[b]Aerosol particle sizer (Model 3321, TSI Inc., Shoreview, MN, USA).
[c]Condensation particle counter (Model 3022A, TSI Inc., Shoreview, MN, USA).
[d]DataRAM 2000 (ThermoElectron Corp., Franklin, MA, USA).
[e]Fluorescence spectrometer (Model FD-500, GTI, Concord, MA, USA).
[f]Nanoparticle surface area monitor (Model 3550, TSI Inc., Shoreview, MN, USA).
[g]Model 1003-AH Dasibi Environmental Corp., Glendale, CA, USA.
[h]Photoelectric aerosol sensor (Model PAS 2000 CE, EcoChem, League City, TX, USA).
[i]Scanning mobility particle spectrometer (Model 3936, TSI Inc., Shoreview, MN, USA).

were used for the measurement of particle size distributions in both laboratory and field studies of VACES and ESP. The SMPS is able to measure the particle size distribution from 16 to 640 nm in mobility diameter, while the APS measures in the range of 0.5–20 μm in aerodynamic diameter. In the same tests the total number concentration was measured with a condensation particle counter (CPC; Model 3022, TSI Inc., Shoreview, MN, USA). Since the operational flow rate of the ESP (1.8 l/min) was clearly lower than that of the APS (i.e., 5 l/min), the APS intake air was diluted by particle-free HEPA-filtered air. The SMPS was operated in low flow mode (i.e., 0.3 l/min) in parallel with the APS. An Ozone Monitor (Model 1003-AH Dasibi Environmental Corp., Glendale, CA, USA) was used in the laboratory studies to measure the ozone production by the ESP corona needles. Ozone concentration was measured at different ESP voltages.

The collection efficiency of the ESP was tested by generating monodisperse fluorescent particles (Polyscience Inc.,Warrington, PA, USA) of various sizes. The fluorescent particles were collected on aluminum foil that was placed on the ground electrode of the ESP. In addition, aerosol samples taken upstream (reference) and downstream (backup) of the ESP were collected on Teflon filters (2 μm pore, PTFE, Pall Corp., East Hills, NY, USA). The aluminum foil and filters were extracted with 9 and 3 ml, respectively, of ethyl acetate and analyzed with a fluorescence spectrometer (Fluorescence Detector FD-500, GTI, Concord, MA, USA). More details of this analysis technique can be found in Sioutas, Kim, and Chang (1999).

Following the laboratory experiments, the VACES with tandem-VI system was deployed inside the particle instrumentation unit (PIU) trailer of the Southern California Supersite. The PIU is located in an urban/industrial area about 100 m downwind of a major freeway and about 3 km south of downtown Los Angeles, CA. The concentration enrichment of outdoor air particles by the VACES with tandem-VI was measured alternately upstream and downstream of the system with various aerosol devices (Table 1). In addition to the SMPS and APS, several other instruments (Table 1) were used for the measurement of different particle parameters: A DataRAM nephelometer (DR-2000, ThermoElectron Corp., Waltham, MA, USA) measured the mass concentrations of sampled particles, whereas continuous measurements of black carbon were performed using an Aethalometer (Model AE-21 (UV + BC), Thermo Andersen, Smyrna, GA, USA). The nanoparticle surface area monitor (NSAM, Model 3550, TSI, Shoreview, MN, USA) was used to measure the active surface area of the collected particles (the sampler measures the active or Fuchs surface area of PM in the 0.01–1 μm range). The operating principle of NSAM is based on diffusion charging of sampled particles, which are detected by using an electrometer. The level of particle-bound polycyclic aromatic hydrocarbons (PAHs) was determined using a photoelectric aerosol sensor (Model PAS 2000 CE, Ecochem, League City, TX, USA) that works on the principle of photo-ionization of the PAH molecules adsorbed on the particle surface. The wavelength of the light in

the PAS is chosen such that only the PAH coated aerosols are ionized, while gas molecules and non-carbon aerosols remain neutral.

3. Results and discussion

3.1. Laboratory validation of a new ESP

3.1.1. Particle penetration vs. ozone production

In the first set of experiments, the ESP was tested in the USC aerosol laboratory by sampling indoor air and measuring its total particle number and ozone concentrations in parallel. According to previous studies (Arnold, Viggiano, & Morris, 1997; Volckens & Leith, 2002), high voltage electrical fields and corona discharges are known to generate ozone and oxidant ions such as O_2^+, O^+, N_2^+, N^+, NO^+ and H_3O^+. Ozone, being a gas with no net charge, predominantly penetrates the ESP whereas corona-created free radicals and ions with high electrical mobility have a higher potential to reach and react with the particles collected on the ESP substrate (Volckens & Leith, 2002). Ozone (and oxidant ions) production by corona discharge in an ESP depends on a number of factors, including the sampling flow rate, relative humidity, material and diameter of corona wire as well as the operational voltage and polarity of a corona (Cardello, Volckens, Tolocka, Wiener, & Buckley, 2002; Goheen, Larkin, & Bissell, 1984; Kulkarni, Namiki, Otani, & Biswas, 2002; Volckens & Leith, 2002). The results of this test are presented as a function of ESP electric field (E_{ESP}) in Fig. 2. Only positive ESP voltage was applied in this study since previous studies have shown that negative coronas produce significantly higher ozone than positive (e.g., Chen & Davidson, 2003). The initial ozone concentration (at 0 kV/cm) of sampled indoor air was in the range of 16–20 ppb, which increased slightly to 30 ppb at E_{ESP} of 5.0–5.3 kV/cm. Subsequently, the ozone concentration increased linearly with E_{ESP}, reaching a maximum of 86 ppb at 6.3 kV/cm.

Particle number concentration decreases slowly when E_{ESP} is increased from 0 to 4.3 kV/cm. Corona discharge is initiated at E_{ESP} between 4.3 and 4.7 kV/cm, which results in a marked decrease in particle penetration. Particle penetration is less than 10% at 5.7 kV/cm, and increasing field strength beyond this point results in little gain in efficiency. Based on these results (Fig. 3), the ideal operational E_{ESP} (i.e., combining a high particle collection efficiency and the lowest possible ozone generation) was chosen to be 5.3 kV/cm, and has been applied in the experiments described in subsequent sections, unless otherwise mentioned. Due to relatively low ozone generation (indicating also the low level of other oxidant ions) and short contact time (of about 10 s) between the particulate and gaseous phases under the selected conditions, it is reasonable to assume that the ESP may not alter the chemical composition of collected particles. This will be verified in a future publication on the chemical characteristics of the system.

In addition to indoor air, the penetration of two different sizes (0.16 and 2.0 μm) of PSL and ammonium sulfate particles was investigated at different E_{ESP}. They displayed a similar pattern to that observed with the total number concentration of indoor air particles (Fig. 2).

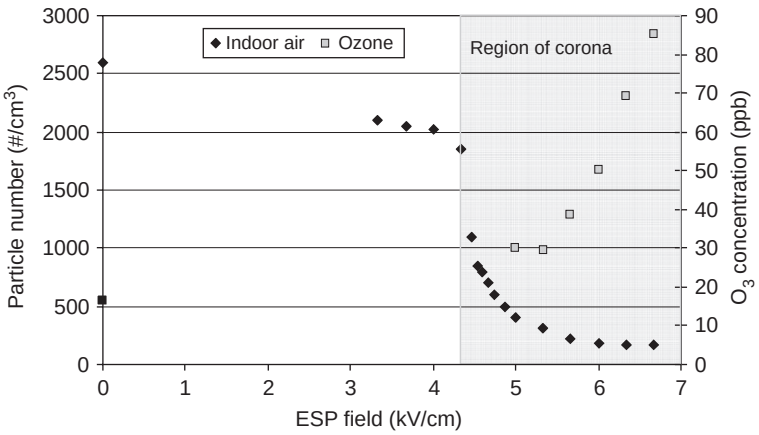

Fig. 2. The indoor air particle number and ozone concentrations as a function of ESP field intensity at the sampling flow rate of 2.3 l/min. The indoor particle number and ozone concentrations have been shown at 0 kV/cm (on the y-axis).

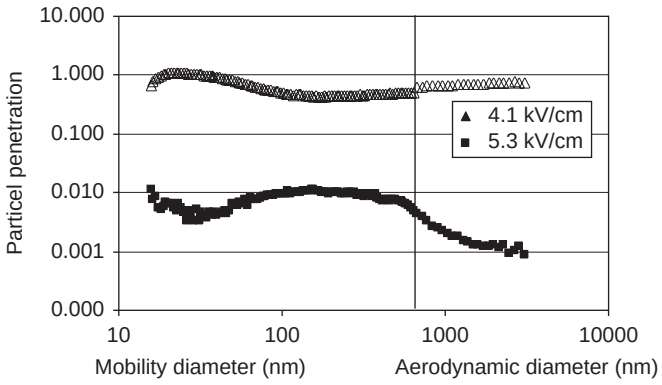

Fig. 3. Penetration of generated 16 nm to 3 μm ammonium sulfate particles at two different ESP field intensities (1.8 l/min).

3.1.2. Particle penetration as a function of particle diameter

In the next set of experiments, the ESP was tested by generating polydispersed ammonium sulfate in the USC aerosol laboratory, selecting different voltages and scanning the downstream particle number concentration with the SMPS and APS. Fig. 3 shows the particle penetration as a function of particle diameter at two E_{ESP}. The penetration over the investigated particle range varies between 43–100% at 4.1 kV/cm and 0.3–1.1% at 5.3 kV/cm. After E_{ESP} of 4.7 kV/cm, the penetration change was minimal, with the means ±SD being $1.0 \pm 0.3\%$ at 5.1 kV/cm, $0.8 \pm 0.2\%$ at 5.3 kV/cm and $0.3 \pm 0.1\%$ at 5.9 kV/cm, respectively.

After the corona discharge was initiated, the particle penetration displayed a similar pattern at different E_{ESP}. The penetration reached the local minimum values for the particles close to 30 nm in mobility diameter and super-micron particles, whereas the local maximum value occurred for particles between 100 and 200 nm in mobility diameter. In the particle size range < 30 nm, the increasing penetration with decreasing particle diameter is most likely due to insufficient or incomplete particle charging of that size range (Zhuang, Kim, Lee, & Biswas, 2000). Diffusion charging is the dominant mechanism for particles smaller than 0.1 μm, whereas field charging is the dominant mechanism for particles larger than 1.0 μm. Accumulation mode particles ($0.1\ \mu m < D_p < 1.0\ \mu m$) between these two size ranges are charged through both mechanisms, and typically the collection efficiency is lowest for these particles (Hinds, 1999). However, the results of this study suggest that the capture efficiency (~99%) of the ESP did not depend significantly on the particle size under the operational conditions.

In addition to ammonium sulfate particles, particle number size distributions (16–638 nm) of polydispersed glutaric acid and indoor air were measured after the ESP at E_{ESP} of 0 and 5.3 kV/cm. The size distributions and the corresponding penetration plots are presented in Fig. 4. The number mode diameter of generated glutaric acid particles was 60 nm, whereas the modes of ammonium sulfate and indoor air particles were 150 and 130 nm, respectively. Since electrical resistivity varies considerably with material composition, collection efficiency can fluctuate as the chemical composition of the collected particles changes (Zhuang et al., 2000). However, our results show that particle penetration is $< 5\%$, independently of particle composition and size (Fig. 4). This corroborates the results of Fig. 3, showing the very high charging and collection efficiency of nanoparticles, which are typically the most difficult to charge.

3.1.3. Collection efficiency of the ESP

The collection efficiency of the ESP was investigated experimentally by collecting samples on both up- and downstream filters as well as on a filter placed on the ESP collection plate. This test was conducted to confirm that particles are being collected on the targeted collection plate and not being lost elsewhere inside the ESP. The results based on the fluorescence analysis are presented in Fig. 5. The capture efficiency (black bar) is equal to the particle fraction that does not penetrate through the ESP, whereas the collection efficiency (gray bar) depicts the fraction of particles depositing on the collection plate. The mass balance, based on the ratio of the sum of ESP line values to a parallel reference filter value, was within 4% for all three particle sizes tested. Any difference between these two bars equates to particle losses occurring inside the ESP. Fig. 5 shows that overall collection efficiency of fluorescent PSL particles is similar to that which is reported in Fig. 3, and nearly all of the particles are collected on the target plate. Thus, particle losses inside the ESP are negligible ($< 1\%$) for all particle sizes tested.

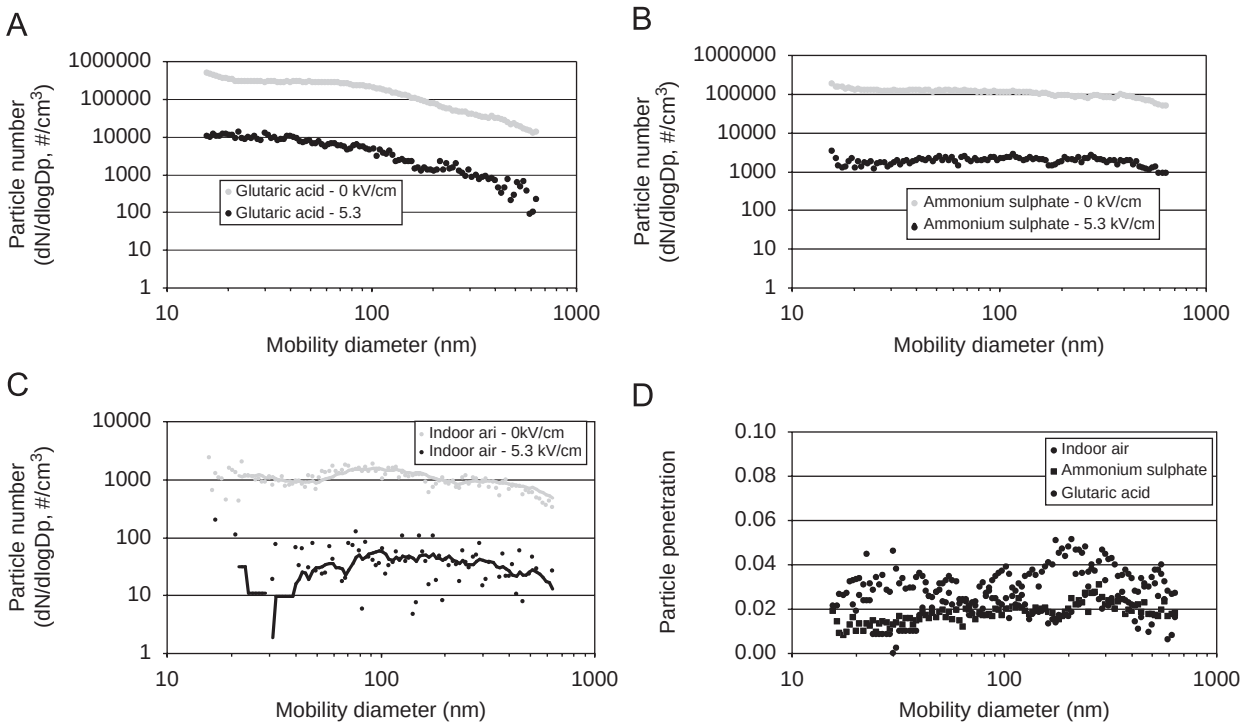

Fig. 4. Number size distribution of penetrated glutaric acid (A), ammonium sulfate (B) and indoor air (C) particles at 0 and 5.3 kV/cm as well as their penetration curves (D) at 5.3 kV/cm (1.8 l/min). The lines in (C) depict the 10-point moving averages.

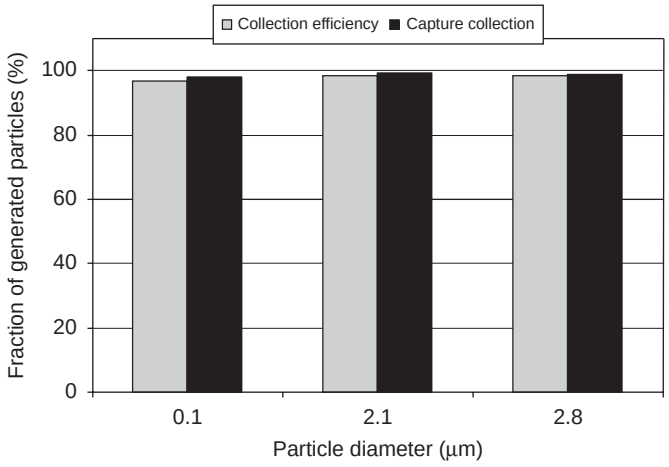

Fig. 5. The collection efficiency of the ESP with three different sizes of fluorescent particles at the ESP field intensity of 5.0 kV/cm and sampling flow rate of 1.8 l/min.

3.1.4. Cell exposure tests

Since this technology was developed primarily to expose in vitro live cells to ambient PM, it was necessary to determine any possible harmful effects of the ESP electrical field to these. Mouse macrophages (RAW 264.7) were exposed to E_{ESP} of 5.3 kV/cm for typical exposure intervals. In the first test the glass petri dish (∅9 cm) was placed on the ground electrode under the corona needles. The presence of the glass petri dish plus cell culture had no influence in the collection efficiency of the ESP. The cells were exposed to HEPA-filtered clean indoor air for 60 min. It should be

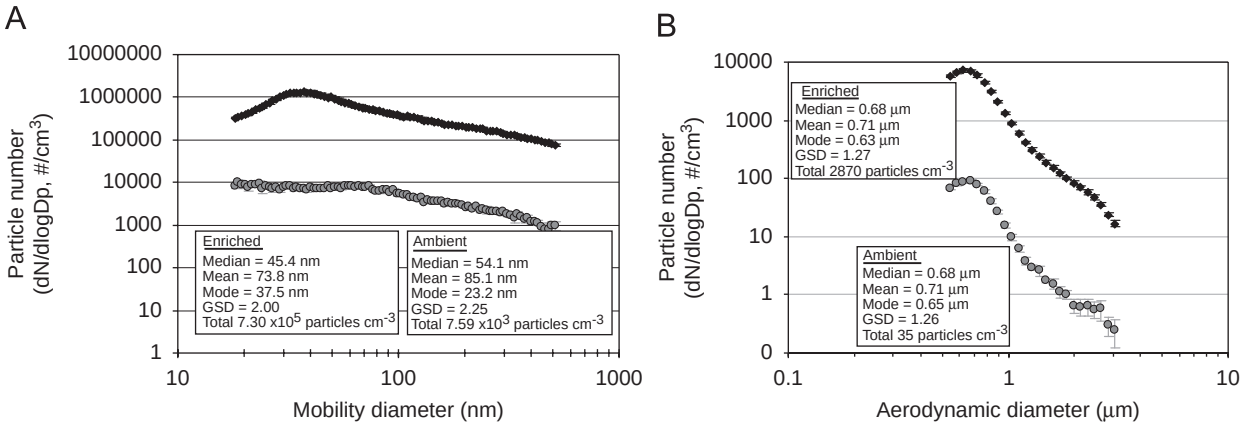

Fig. 6. The number size distribution of ambient and VACES enriched particles measured simultaneously with the SMPS (A) and APS (B) at PIU sampling site.

noted that ambient gases were introduced in our system at their ambient levels, without any attempt to remove them. Immediately after the exposure, cellular viability was assessed by trypan blue staining. Since the first exposure had no adverse effect on cell viability, the second cellular exposure test was performed for 120 min. Additionally, the cell suspension in the latter test was grounded with a sterilized copper wire by dipping its one end into the culture medium and fixing its other end to the bottom electrode. After the latter test, 96% of the cells remained viable. This is not a substantial change in cellular viability because similar percentage was also observed in unexposed control tests. Thus, it can be concluded that the ESP did not have a harmful effect on cell viability under the operational conditions.

3.2. Field test of particle concentrator

Upon completion of the laboratory validation of the ESP, the particle concentrator was tested at a sampling site near downtown Los Angeles. Because the ESP's nominal flow rate is low ($\leqslant 5$ l/min), the particle concentration system must be coupled with the ESP for cell exposure to sufficiently high loadings of ambient air particles within 1–2 h. At locations with high particulate concentrations (i.e., dynamometer facilities, or areas in close proximity to a PM source), the ESP may be used alone. In this study, however, the traditional VACES was altered by adding a second VI in series with the original system (Fig. 1). The performance of the VACES with tandem-VI was verified by measuring the pre- and post-enriched PM parameters with various instruments.

3.2.1. Number size distribution of ambient and enriched particles

Fig. 6 presents the average number size distributions of ambient and enriched particles. The total number concentrations of ambient particles measured with the SMPS and APS were 7590 and 35 cm^{-3}, respectively. After concentration enrichment, the corresponding number concentrations were 730 000 and 2870 cm^{-3}. Based on these measurements, the enrichment factor of the VACES with tandem-VI was 96 and 82, respectively (Fig. 6). The median, mean and mode of the number size distribution of ambient particles between 0.54 and 3.0 μm in aerodynamic diameter (Fig. 6B) changed by less than 3% after enrichment by the VACES with tandem-VI. This indicates that concentration enrichment does not change substantially the original number size distribution in this particle size range. While investigating particles between 18 and 514 nm in mobility diameter (Fig. 6A), the ambient and enriched number size distributions were more variable. First the enrichment factor increased from 31 to 70 with increasing mobility diameter for particles between 18 and 25 nm. It is well known that the VACES has a 50% concentration efficiency at around 20 nm due to increased difficulty in activating particles as they decrease in size (Kim, Jaques, Chang, Froines, et al., 2001). Based on the data plotted in Fig. 6, the "50% cutpoint" or half of the ideal enrichment value (e.g., 50 of 100) of the tandem virtual impaction system is at about 22 nm in mobility diameter. The enrichment factor is 70 or higher for particles larger than 25 nm. However, between 29 and 55 nm, particles are enriched by a factor that is slightly higher than the ideal. This cannot be due to particle coagulation since the experimental results show that total enriched particle concentrations were

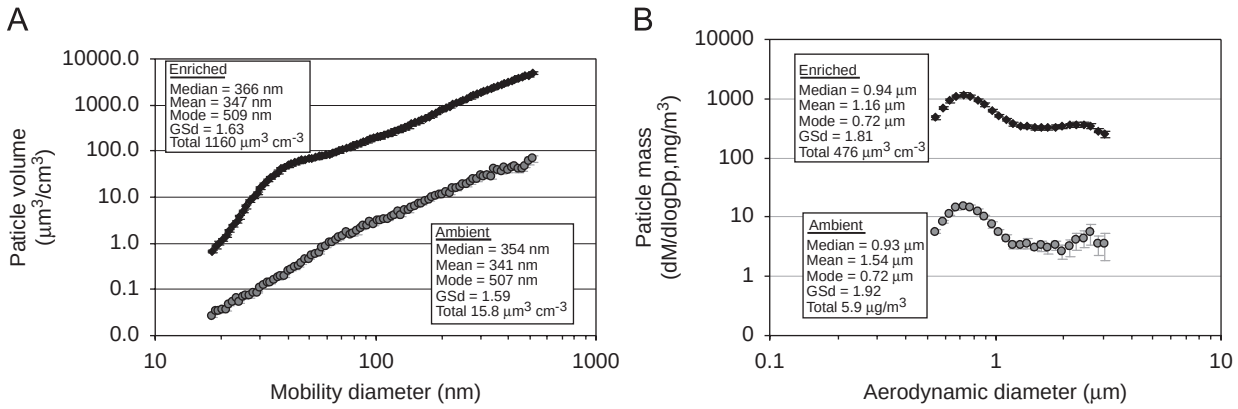

Fig. 7. The volume/mass size distribution of ambient and VACES enriched particles measured simultaneously with the SMPS (A) and APS (B) at PIU sampling site.

Table 2
Concentration enrichment factor (EF) of tandem-VI determined by different instruments

Instrument	Ambient conc.		Enriched conc.		Flow rate (l/min)	Ideal EF	Experimental EF	
	Mean	SD	Mean	SD			Mean	SD
CPC (# cm^{-3})	19 500	4040	2 080 000	3 41 000	1.7	118	106	28
DataRAM ($\mu g/m^3$)	75.4	3.4	5520	281	2	100	73	5
NSAM ($\mu m^2/cm^3$)	33.1	2.6	3080	120	2.5	80	93	8
PAS (ng/m^3)	5.67	1.03	685	41	1.0 + 1.0	100	121	23
Aethalometer-BC ($\mu g/m^3$)	1.27	0.45	100	1	1.8	111	79	28
Aethalometer-UV ($\mu g/m^3$)	1.37	0.10	108	12	1.8	111	79	11

measured at predicted levels. Coagulation would have substantially decreased the number concentration of enriched particles, and enrichment would have dropped as a result. One possible explanation for the increased enrichment of that range may be changes and fluctuation in ambient aerosols concentration that are typical of an urban site affected by the highly variable nearby traffic emissions.

3.2.2. Volume/mass size distribution of ambient and enriched particles

The mass size distributions of ambient and enriched particles are presented in Fig. 7. The average volume concentration of ambient particles based on the SMPS measurements was 15.8 $\mu m^3/cm^3$ while the enrichment by the VACES with tandem-VI increased it to 1160 $\mu m^3/cm^3$, which equates to an enrichment factor of 73. Based on the APS measurements performed in parallel with the SMPS, the mass concentrations of ambient and enriched particles were 5.9 and 476 $\mu g/m^3$, respectively, and thus the enrichment factor was 81. The modal parameters determined from both SMPS and APS data show that the original size distribution of ambient particles did not change during concentration enrichment. Results indicate that the VACES with tandem-VIs concentrates efficiently both number and mass of ambient particles. Furthermore, they show that smaller particles (20–100 nm), which dominate total particle number in typical urban environments, are concentrated as efficiently as larger particles (1–2.5 µm), which dominate total particle mass.

3.2.3. Concentration enrichment factor measured with various instruments

In addition to the SMPS and APS measurements, the performance of the VACES with tandem-VIs was verified with several other instruments, and the results are presented in Table 2. The ambient number concentration was enriched by the VACES with tandem-VI from 19 500 particles/cm^3 to 2.08 × 10^6 particles/cm^3, a factor of 106 of a maximum of 118. The ambient mass concentration was increased from 75.4 to 5520 $\mu g/m^3$, a factor of 73 out of a maximum of 100.

These discrepancies are well within the experimental error of the measurements (CPC and DataRAM) and the variability from experiment-to-experiment in the ambient aerosol concentrations. The enrichment factors based on the surface area-related measurements (NSAM and PAS) were slightly higher than their corresponding theoretical factors (Table 2). The discrepancies may be due to variable ambient concentrations or possible measurement error due to non-linearity of the instrumental responses over the order of magnitude differences between ambient and concentrated aerosols. Finally, the concentration enrichment of the VACES with tandem-VI was determined with a two-channel Aethalometer. The ambient $PM_{2.5}$ black carbon averaged around 1.37 $\mu g/m^3$ during this run (Table 2). After enrichment, the concentration averaged approximately 100 $\mu g/m^3$, which is somewhat less but still close to the expected enrichment factor of 111. The enrichment factors based on the BC and UV measurements were equal.

All the results presented in Table 2 show that the particle concentrator system in question may be used with high efficiency to enrich ambient particles for ESP collection. When a lower enrichment factor is desirable or sufficient for the incoming aerosol to be collected by the ESP, the VACES configuration described by Kim, Jaques, Chang, Froines, et al. (2001) and Kim, Jaques, Chang, Barone, et al. (2001) producing an aerosol concentration enrichment of about 30 can be used instead of tandem-VI.

4. Summary and conclusions

This study presented a new sampling system to collect ambient particles for in vitro studies. The in vitro electrostatic collector consists of two units: a versatile aerosol concentration enrichment system (VACES) and a new design of electrostatic precipitator (ESP). The optimized ESP field intensity at sampling flow rate of 1.8 l/min was found to be 5.3 kV/cm. The optimization was based on balancing high collection efficiency with low ozone production. The laboratory tests with monodisperse polystyrenelatexparticles and polydispersed ammonium sulfate and glutaric acid particles as well as indoor air showed that the collection efficiency does not depend significantly on particle composition. The collection efficiency under optimized conditions is higher than 95% across all particle diameters measured (18 nm to 3.0 μm), and particle losses inside the ESP were negligible ($< 1\%$). Additionally, the ESP was shown to have no harmful effect on cell viability during 2-h cell exposure.

For in vitro studies with ambient air, the ESP must be coupled with an aerosol concentrator in order to minimize the cell exposure time. Based on the size distribution measurements of ambient and corresponding enriched particles, the use of the VACES with tandem-VI concentrated ambient particles by a factor of 80–100 and did not substantially change the original particle composition. Thus, the cell petri dish (I.D. 10 cm) placed inside the ESP can be exposed to 3×10^{11} particles while collecting typical urban air (20 000 particles/cm^{-3}) with the in vitro electrostatic collector for 2 h.

There are significant advantages of in vitro electrostatic collector over the technologies that are currently considered state-of-the-art. The first advantage is the use of a previously developed particle concentration system to deliver concentrated ambient particles (by 80–100 times) to the ESP for in vitro cell exposure. This allows for shorter sampling durations, which benefits cells that might not be viable after prolonged exposure to the sampling environment. Shorter time interval sampling also enables discovery of possible relationships between health effects and time of day or short-term source emissions. The main advantage of in vitro electrostatic collector is that it collects $> 95\%$ of particles—regardless of particle type or diameter—directly to a target area, on which a cell culture can be placed. The unique design implements two metal needles to facilitate a corona discharge, resulting in high particle charging efficiency with little ozone production. These advantages make the in vitro electrostatic collector a viable in vitro cell exposure technique.

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