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A study of ionization and collection efficiencies in electrospray-based electrostatic precipitators

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Abstract

Ozone-free electrostatic precipitators incorporating an array of electrospray wick charged aerosol ionization sources were built and tested. The particle ionization and collection efficiencies were independently measured for airborne particles as a function of air flow rate, electric field magnitude, and particle size. The results indicate that, while particle ionization efficiencies near 100% can be achieved using the electrospray ionization method, the number of elemental charges deposited onto a given particle depends strongly on the particle diameter and for submicron particles is very low. High overall particle collection efficiency, therefore, requires a carefully designed precipitation region where the maximum particle collection time, associated with the particles with the lowest mobility, is less than the residence time within the collector.

Keywords: Electrospray; Air purification; Electrostatic precipitation

1. Introduction

Air purification systems based on electrostatic precipitation (ESP) have been used for years in both industrial and commercial applications and typically employ a corona discharge to ionize air contaminants and a series of metal plates to collect the ionized species (Jaworek, Krupa, & Czech, 2007). The popularity of ESP systems is due, in part, to a combination of quiet operation and low maintenance (e.g. no filter replacement). However, the corona ionization process produces ozone and the usefulness of these systems has come into question because of health concerns (Hazucha & Lefohn, 2007).

Recently, we reported on the development of ozone-free electrostatic precipitation systems employing an array of electrospray wick charged aerosol sources for particle ionization (Tepper, Kessick, & Pestov, 2007). Electrospray aerosols are used in applications such as analytical chemistry (Fenn, Mann, Meng, Wong, & Whitehouse, 1989), particle generation (Rulison & Flagan, 1994), coatings (Seaver & Eckhardt, 1988), and space propulsion (Bartoli, von Rohden, Thompson, & Blommers, 1984). Typically, in what is known as the cone-jet mode of electrospraying, a jet of charged

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liquid emerges from the tip of a single conical protrusion known as a Taylor cone, which is formed at a liquid surface through a competition between an applied electric force and the liquid surface tension (DelaMora, 2007). The charged liquid jet is unstable and eventually breaks up into a plume of charged liquid droplets. The initial droplet diameter is determined by various parameters including the liquid conductivity, surface tension, flow rate and the diameter of the spraying orifice and is typically just a few microns (Ganan-Calvo, Davila, & Barrero, 1997; Gomez & Tang, 1994). As the droplets shrink due to solvent evaporation, they undergo a series of Coulombic explosions when the electrostatic repulsive force on the surface of the charged droplet exceeds the liquid surface tension. This process repeats and produces a charged aerosol of nanoscale droplets, which can be used for the ionization and collection of gas-phase contaminants (Tepper, Fenn, Kessick, Pestov, & Anderson, 2006).

In addition to conventional electrospray sources, nanoelectrospray (NanoES) sources (Wilm & Mann, 1996) and polymer monolith sources (Koerner, Turck, Brown, & Oleschuk, 2004) have been reported for applications in mass spectrometry and microfluidics. In both NanoES and polymer monolith sources, the effective diameter of the spraying orifice is greatly reduced thereby reducing the initial droplet diameter and liquid flow rate. The liquid flow in these sources is driven primarily by capillary forces thus eliminating the need for solvent pumps. However, fabrication of NanoES or polymer monolith sources is relatively cumbersome, requiring either drawing and tapering the orifice diameter to about 1 μm or a polymerization reaction within a microcapillary. Therefore, we used porous polymer wicking materials from commercial vendors such as the Porex or Filtrona Corporations as electrospray aerosol sources. Porous polymer wicking materials such as bonded synthetic fibers are currently used in applications such as air fresheners, ink jet printers, filters, and medical testing kits. These low-cost, wettable, porous materials are available in a variety of shapes, sizes, and porosities and we found them to be ideal electrospray aerosol sources for applications in air purification.

In our previous electrospray-based ESP systems, the particle ionization and collection steps were integrated making it difficult to separately quantify particle ionization and collection efficiencies. However, the overall particle removal efficiencies were quite promising and clean air delivery rates (CADR) greater than 100 for both dust and cigarette smoke were achieved (Tepper et al., 2007). The CADR number is used by the Association of Home Appliance Manufacturers (AHAM) to quantify and compare the performance of commercial air purification systems and, as a rule of thumb, should be at least $\frac{2}{3}$ the square footage of the room being purified. Here we report on a quantitative evaluation of the particle ionization and collection efficiencies in electrospray-based ESP systems with separate particle ionization and collection regions.

2. Experimental

Two prototype air purification systems, one small and one large, were constructed and tested. In each system, particle ionization was accomplished by charge transfer from an aerosol of charged droplets dispersed into an air stream from an array of electrospray polymer wick sources. Wick electrospray sources were employed instead of conventional hollow needles in order to eliminate the need for mechanical components such as syringe pumps and valves and to uniformly distribute the charged aerosols throughout an air flow channel. A wick is self-balancing and, through capillary action, will automatically replenish the solvent dispersed by the electrospray aerosol. The wicks consist of a microporous, bonded synthetic polymer material from two commercial vendors; Filtrona and Porex Corporations. The wicks from Filtrona were 2 mm in diameter and the wicks from Porex were 1 mm in diameter. The wicks were cut to a length of about 20 mm and wetted by placing one end into a liquid reservoir containing a 90/10 water/ethanol solution. Electrospray was initiated by applying a high voltage between the liquid reservoir and a counter electrode located opposite the wick tip, which could be either blunt or cut to a 45° bevel to enhance the local electric field magnitude.

Fig. 1 is a plot of the electrospray current versus the applied potential difference between a blunt wick tip and a grounded counter electrode located at a distance of 1 cm for a 1 mm Porex and 2 mm Filtrona wick. For both wicks, the electrospray current initially increases with applied voltage as expected, but then levels off and stays relatively constant until reaching the point of corona discharge where the current increases dramatically. Due to the higher electric field concentration in the smaller diameter Porex wick, the electrospray initiates at a lower voltage and the onset of corona discharge also occurs at a lower voltage (7.2 kV versus 8.4 kV).

The current–voltage characteristics of the wick sources depends on several factors including the wick diameter and porosity and the solvent viscosity and surface tension and two primary spray modes were observed. In the first mode, when the maximum wicking rate of the porous polymer as determined by the Washburn (1921) equation exceeds the