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A novel electrical-mobility-based instrument for total number concentration measurements of ultrafine particles

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ABSTRACT

A novel electrical-mobility-based technique to measure total particle number concentration over a selected size range is presented. Charged particles are condensed out onto an electrode that is shaped such that the product of its transfer function and the particle charging efficiency is a constant, independent of particle size. The resulting total current is then proportional to the number concentration of the sampled particles over the collected size range. The theoretical approach for the calculation of the electrode shape function is described. The extension of this technique for measurement of higher moments of the particle size distributions over a desired size range is briefly discussed.

This concept is used to design a new instrument, called the tailored electrode concentration sensor (TECS). For validation of the theoretical concept, the collection electrode in the TECS instrument is designed for concentration measurements over a size range of 30–90 nm. In the TECS, the collection section is located downstream of an electrostatic precipitator section, where the sampled flow is split into aerosol and sheath flows, similar to the design of the MEAS [Ranjan, M., & Dhaniyala, S., (2007), Theory and design of a new miniature electrical-mobility aerosol spectrometer, *Journal of Aerosol Science*, 38(9), 950–963]. This results in a compact, low pressure drop instrument. Experimental results confirm that the response of the optimally-shaped electrode in the TECS system is only proportional to total number concentration over the selected size range.

1. Introduction

Ambient ultrafine particles (UFP, particle diameter, $D_g < 100$ nm) make only a small contribution to the $PM_{2.5}$ mass, but constitute a significant fraction of particulate number (Westerdahl, Fruin, Sax, Fine, & Sioutas, 2005; Bukowiecki et al., 2002). UFPs are more likely to reach and reside in the gas-exchange region of the lung and present a greater interactive surface per unit mass of inhaled material than larger particles (Seaton, MacNee, Donaldson, & Godden, 1995; Oberdorster, Ferin, & Lehnert, 1994). In urban areas, UFPs are predominantly formed due to combustion activities and, thus, have compositions that are likely to adversely affect human health (Elder, Gelein, Finkelstein, Cox, & Oberdörster, 2000; Donaldson, Li, & MacNee, 1998; Peters, Wichmann, & Tuch, 1997; Ferin, Oberdorster, & Penney, 1992). It has been speculated that significant exposure to UFPs could possibly result in fibrosis and lung cancer (Mauderly, 1996), aggravating asthma, and inducing heart rate variability (Frampton et al., 2004; Frampton, 2001).

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The short lifetimes of UFPs result in significant inhomogeneity in their spatial and temporal distribution (Martuzevicius et al., 2004). In particular, UFP number concentrations can vary significantly over short distances (Zhu et al., 2002). This complicates assessment of public exposure to ultrafine particles based on data from a few fixed monitoring sites (Violante et al., 2006; Kim, Okuyama, & Shimada (2002); Leung & Harrison, 1998). Estimating indoor exposures to UFPs is further complicated by the transformation of these particles as they traverse the indoor-outdoor boundary and due to the presence of indoor sources (Zhu et al., 2005).

Complete characterization of exposure to UFPs will require measurements at a large number of locations (Eulerian measurements) or along all points of interest (Lagrangian). Accurate UFP number concentration measurements are possible with existing commercial instruments such as the scanning mobility particle sizer (SMPS) and fast mobility particle spectrometer (FMPS; TSI Inc.). These instruments are, however, very expensive for large scale Eulerian measurements and their large size and need for electrical power prohibits their deployment for Lagrangian measurements. Also, while these instruments provide high size-resolution information, a single measure of total ultrafine number is, often, sufficient for monitoring and health assessment studies.

Total particle number measurements are possible with a portable condensation particle counter (e.g., TSI 3007 CPC). CPC measurements are, however, not limited to particles in the ultrafine size range. This might be possible by combining the CPC with an upstream impactor of a 100 nm cut-size. This instrument would, however, have a high pressure drop, and thus require a larger pump. Also the resultant lowering of internal pressure will negatively affect instrument performance. Also, portable CPCs have a size dependent counting efficiency, with low detection efficiency for particle sizes less than ~30 nm. This complicates total number measurements with these instruments (Zhu, Yu, Kuhn, & Hinds, 2006). In addition, small fluctuations in CPC sample flow rate or pressure can result in complicating CPC operation due to liquid overflow (Birmili et al., 1997; Hermann & Wiedensohler, 1996). Measurements with portable CPCs will also be compromised by their low upper concentration limit (10^5 cm^{-3}). In addition, remote, long-term monitoring with CPCs is complicated by the need for regular maintenance to ensure that their working fluid levels are maintained. There is an immediate need for a compact, portable, inexpensive, and easy to deploy UFP concentration measurement instrument which could be used for large-scale indoor/outdoor monitoring and personal sampling studies.

Recently, the design and working of a compact instrument called the miniature electrical-mobility aerosol spectrometer (MEAS; Ranjan & Dhaniyala, 2007, 2008) was presented for ultrafine size distribution measurements. Here, we extend that concept to design a new compact, portable, instrument that can provide real-time total particle concentration over a desired size range.

2. Background

The design of a compact, portable total concentration sensor, called the tailored electrode concentration sensor (TECS) is introduced, based on the concept of the MEAS instrument (Ranjan & Dhaniyala, 2007, 2008). The MEAS instrument consists of three sections—inlet; electrostatic precipitator (ESP); and a classifier section (Fig. 1). For sizing with MEAS, particles are charged upstream of the instrument with a bipolar charger and enter the instrument through the inlet section. The inlet section is designed to ensure a uniform spatial distribution of particle concentration as they enter the ESP section. In the ESP section, particles pass through a set of parallel plate channels that are maintained at desired electric potential differences. Charged particles are electrostatically filtered from all channels, except one, the injection channel. The flow through this injection channel forms the aerosol flow in the classifier section, while the flow between the injection channel and the collection electrode acts as sheath flow. In the classifier section, an electric potential difference is maintained to classify the injected particles based on their electrical mobility and particles are collected in a series of rectangular-shaped collection plates or electrodes that are connected to electrometers. A size distribution can be obtained from the electrometer signals with the knowledge of particle collection characteristics of the different electrodes (Ranjan & Dhaniyala, 2008).

The simple, open design of the MEAS results in a low-pressure-drop instrument, requiring control of just one flow. For real-time size distribution measurements with MEAS several electrometers are required; thus, potentially increasing its cost and complicating its operation. Often, a single measure of total particle number concentration over a desired size range, such as less than 100 nm, is sufficient. For such applications, based on the MEAS design, a new TECS instrument is introduced, with a single collection plate and, hence, just one electrometer. The complication in the design of such an instrument is to ensure that the electrometer signal is directly proportional to the particle number concentration over the desired size range.

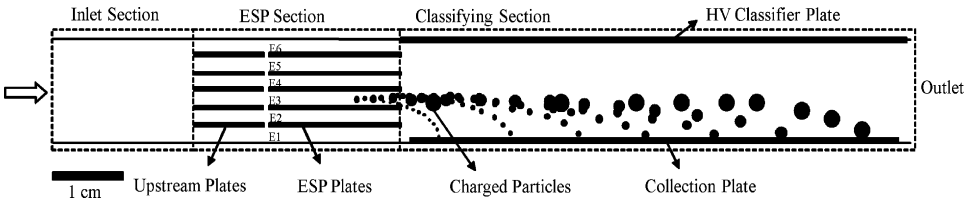

Fig. 1. A cross-sectional view of the TECS/MEAS instrument. Charged particles are injected from one ESP channel (E3) and particles are classified by their electrical mobility in the classifier section.