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Modelling ultrafine/nano particle dispersion in two differential mobility analyzers (M-DMA and L-DMA)

S. Ramechecandane [a,*], C. Beghein [b], F. Allard [b], Pierre Bombardier [c]

[a] WindSim AS, 3115 Tønsberg, Norway
[b] Pole Sciences et Technologie, Universite de La Rochelle, La Rochelle 17000, France
[c] Faure QEI, France

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ABSTRACT

In the present work, the dispersion of ultrafine/nano particles in two differential mobility analyzers (DMA) namely, a medium DMA (M-DMA) and a long DMA (L-DMA) is numerically analyzed using the Lagrangian tracking method. Simplified geometries of the two DMA's (M-DMA and L-DMA) that are truly representative of a wide class of DMAs have been considered for the present analysis. The exact profiles of velocity and electric field are used for conducting the present investigation. The Langevin equation is numerically solved to track the particles inside the DMAs. The Brownian force has been modelled as a Gaussian white noise random process. The effect of Brownian force on the dispersion of ultrafine/nano particles is clearly evident from the present investigation. The performance evaluation of both the DMAs have been carried out by comparing the transfer functions obtained using the present methodology with the widely accepted transfer functions of Knutson & Whitby and Stolzenburg. The numerical results obtained using the present methodology compare quite well with the experimental data available. It is also shown that DMAs with smaller effective electrode lengths have higher collection efficiencies for real nano-sized particles.

1. Introduction

Urbanization and industrialization along with the increased usage of automobiles contribute significantly to air pollution. The pollutants that are released into the atmosphere pose an increased threat to the human health. The pollutants emitted by the combustion of fossil fuels are quite inevitable. The size of the aerosols/pollutants might range from less than a micrometre to a few nanometres. The measurement of such ultrafine/nano particles requires measuring devices of high accuracy and resolution. The classification/sizing of aerosols has remained as a challenging area of research in the past few decades [1–5]. Of the various means of classification/sizing, the electrostatic classification of ultrafine/nano particles proves out to be the most viable and promising technique. The electrostatic classification of ultrafine/nano particles is the process by which the particles are separated into classes according to their electric mobility. Different types of Differential Mobility Analyzers (DMAs) are used for ultrafine/nano particle classification like, Medium DMA, Long DMA, Nano-DMA, and so on. Though the principle of these DMAs remains the same, the inner and outer electrode radii, the size of particles measurable, the injection of the sheath gas might be different in these various variants of DMA.

The present study focuses on a Medium DMA and a Long DMA manufactured by GRIMM, for which we have experimental results. Such DMAs consist of two concentric cylinders, named the classification region. Before entering the DMA, the electrically charged particles are at first subjected to a neutralizer to achieve Boltzmann equilibrium (i.e., equal number of positively and negatively charged particles) (see Figs. 1 and 2). The neutralizer is a TSI neutralizer which uses a radioactive source to ionize the surrounding atmosphere into positive and negative ions. Particles carrying a high charge can discharge by capturing ions of opposite polarity. After a short time, the particles reach charge equilibrium such that the aerosol carries a bipolar distribution.

Particles enter the DMA through an axisymmetric inlet slit located at the top of the outer grounded cylinder. Clean air (sheath gas) flows axially between the two cylinders, under laminar conditions. A positive voltage is applied on the inner cylinder, and thus negatively charged particles migrate towards the inner cylinder. Based on the point of injection, the particle size and the applied voltage, the particles assume different trajectories. The

* Corresponding author. Tel.: +47 33 38 18 00.
E-mail address: ramesh@windsim.com (S. Ramechecandane).

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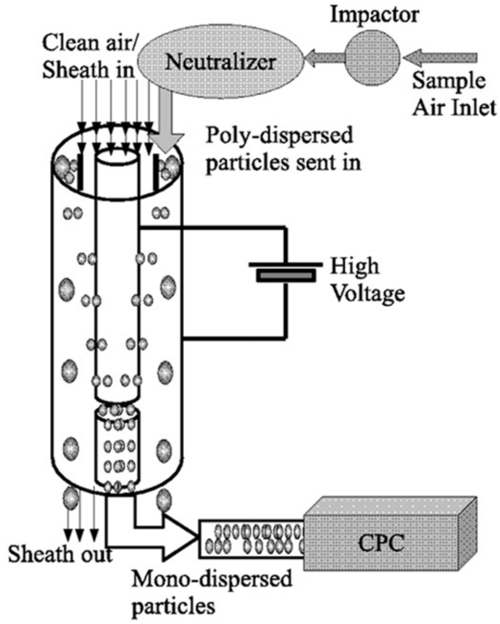

Fig. 1. Experimental set-up ([3]).

particles if smaller than the required size may adhere to the walls of the inner electrode and if larger may traverse beyond the exit slit. Particles of the required size reach the axisymmetric outlet slit located at the bottom of the inner cylinder, and a mono-dispersed aerosol is thus produced.

Only particles with a narrow range of electrical mobility are extracted by the DMA to be measured by the particle sensor. To determine the particle size associated with a range of electrical mobility, the definition of particle electrical mobility must be examined. The electrical mobility is a measure of the particle's ability to move in an electric field. An aerosol particle in an electric field experiences an electrical force, causing it to migrate through the gas in which it is suspended. The drag force on the particle can be equated to the electrical force to determine the electrical mobility of the particle carrying 'n' elementary charges. The electrical mobility Z_P is defined as

$$Z_P = \frac{neC_c}{3\pi\mu D_P} \tag{1}$$

Where, n is the number of elementary charges on the particle, e is the elementary charge ($1.60217733 \times 10^{-19}$ C), C_c is the Cunningham slip correction factor given by

$$C_c = 1 + \frac{2\lambda}{D_P}[1.257 + 0.4\exp(-1.1D_P/2\lambda)] \tag{2}$$

λ is the mean free path of gas, for air $\lambda = 66$ nm at normal temperature and pressure, μ is the dynamic viscosity of the gas, D_P is the particle diameter.

The inner and outer electrode radii for the GRIMM DMAs considered for the present study are 13 mm and 20 mm respectively, whereas the effective electrode length is 88 mm in the case of M-DMA and 350 mm for the L-DMA. The aerosol and the sheath flow rates in both of the DMAs are 0.3 l/m (5×10^{-16} m^3/s) and 3.0 l/m (5×10^{-5} m^3/s) respectively. In the present investigation, air is the sheath gas and the aerosol particles are silver nanoparticles ranging from 5.4 to 358 nm for the M-DMA and 11–1110 nm in the case of L-DMA. The experimental data obtained from the M-DMA and L-DMA is presented in Fig. 3.

As the objective of the present study is to propose a methodology to numerically calculate the applied voltage that corresponds to the maximum collection efficiency of a particular size of particle, due emphasis is given to the numerical part of the work and the experimental details are not presented here for the sake of brevity.

With the increasing power of computers, numerical modelling has been used to elaborate DMAs [3–7]. The aim of the present study is to obtain the experimental curves by a numerical model. To do this, a simplified geometry of the DMA has been considered, as presented in Fig. 4. The Lagrangian technique has been used to track the particles injected at the inlet slit. The laminar flow which is assumed to be fully developed and the electric field between the cylinders (inner and outer electrode) have been calculated by using the analytical expressions for calculating the velocity (fully developed laminar flow) and the electric field between the concentric cylinders, as done by Hagwood et al. [8].

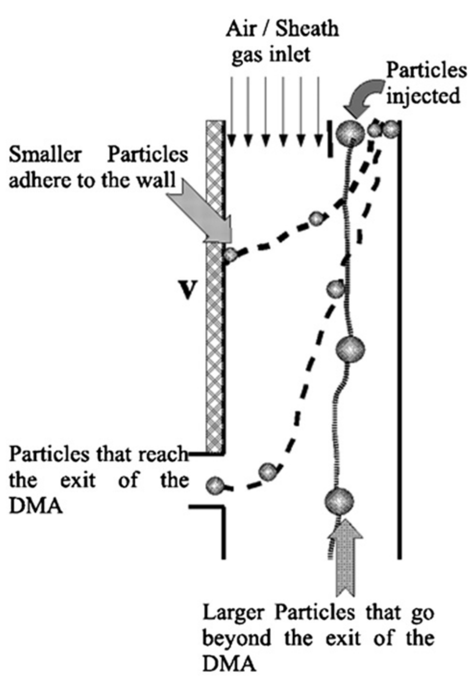

Fig. 2. Schematic representation of particle behaviour inside the DMA ([4,5]).

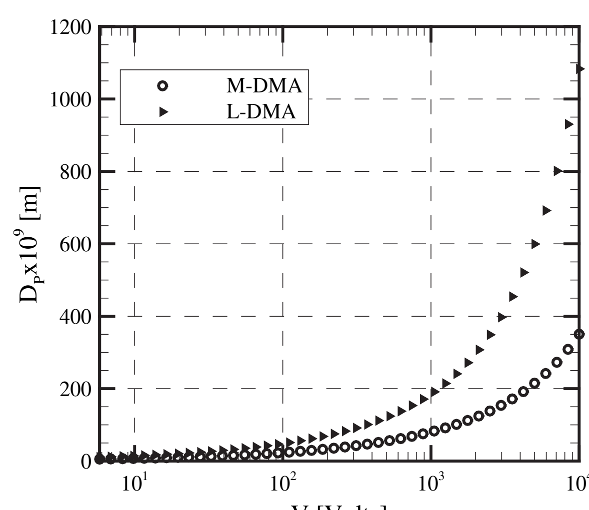

Fig. 3. Experimental data for both the DMAs (M-DMA measurable size range 5.4–358 nm; L-DMA measurable size range 11–1110 nm).