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Determination of the relevant charging parameters for the modeling of unipolar chargers

M. Domat [a,*], F.E. Kruis [b], J.M. Fernandez-Diaz [a]

[a] Department of Physics, University of Oviedo, C/Calvo Sotelo, s/n, E-33007 Oviedo, Spain
[b] Institute for Nanostructures and Technology (NST) and Center for Nanointegration Duisburg-Essen (CENIDE), University of Duisburg-Essen, Bismarckstr. 81, D-47057 Duisburg, Germany

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ABSTRACT

A model for unipolar charging of nanoparticles based on the Fuchs birth-and-death theory is developed. It includes both diffusional and electrical losses for particles and ions. Electrical losses are modeled by inclusion of a radial electric field which is caused by space charge. The model can be used to obtain the initial ion concentration and mean radial electric field from data of charge distribution fractions, without additional measurements. It was successfully applied to results from three different unipolar chargers. In all cases, good agreement between experimental and modeling results has been obtained. The model can be used to assist the operation of unipolar chargers, e.g. by predicting charging efficiencies for particle sizes which are not experimentally accessible.

1. Introduction

Nowadays there is an increasing interest in the production and characterization of nanoparticles. Aerosol particle sizing techniques such as differential mobility analysis are since long the most reliable procedure for obtaining particle size distributions. The data inversion requires however precise knowledge of the charge distribution of the incoming aerosol.

One of the techniques used to charge aerosol particles is diffusion charging. It is a process independent to a great extent of the material, and very efficient. It is commonly used in connection with aerosol instrumentation based on electrical analysis such as ELPI (Electrical Low Pressure Impactor) or EAA (Electrical Aerosol Analyzer), assuming that the aerosol has attained a stable charging state before entering the instrument. Unipolar diffusion chargers based on a corona discharge have been studied for a long time (Alguacil & Alonso, 2006; Biskos et al., 2005a; Büscher et al., 1994; Hewitt, 1957; Intra & Tippayawong, 2010; Kruis & Fissan, 2001; Liu & Pui, 1975; Medved et al., 2000). Due to the absence of ion recombination, they can attain higher charging levels than bipolar chargers. This is usually done by choosing an adequate $N_i t$-product (ion concentration times mean aerosol residence time in the charger). Also, they are exempt from the severe legal restrictions applied to radioactive sources.

The complete modeling of corona chargers is a very complex task, as it bases on a plasma discharge. Therefore, it is usually simplified as an electrodynamic phenomenon in which the electric field is caused by the applied field and the charge dynamics, and for the movement ions it is assumed that they obey the continuity equation. Even then, the solution of the

* Corresponding author.
E-mail address: maida.dro@gmail.com (M. Domat).

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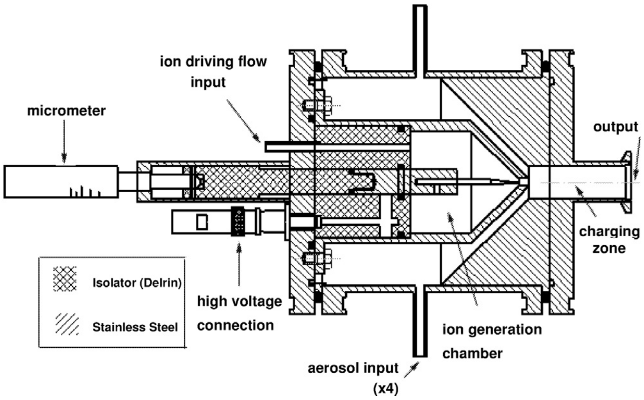

Fig. 1. Schematic figure of the corona charger presented in Domat et al. (2014).

partial differential equations that control the corona is difficult to obtain. It is primarily due to the fact that generation of ions occurs in a tiny area around the sharpest part of an electrode.

There are several methodologies to estimate the charge density of ions and particles. One can cite among others Adamiak & Atten (2004), Dumitran et al. (2008), Khaddour et al. (2008), and Meroth et al. (1999) which show the difficulty of obtaining a numerical solution of the problem. This is related to the multiscale character of the problem: in a micron-sized region, ions are produced and then enter the charging region having sizes in the order of centimeters. When the fluid dynamics is also taken into account, the numerical solution of the charging model is computationally very expensive (between 3 and 48 h for a single simulation, Chien et al., 2011).

If one wants to determine model parameters from experimental measurements, an inversion has to be performed, which prohibits the use of a too complicated numerical model. Therefore, it is necessary to simplify the modeling approach so that an efficient fitting of model parameters can be carried out.

In this study, we apply an extension of the widely used limiting-sphere model of Fuchs (Biskos et al., 2005b; Büscher et al., 1994; Fuchs, 1964) to predict the charge distribution of unipolar chargers with approximately cylindrical symmetry in the charging zone, although it will be shown that can be applied to other geometries and charger types such as the more complex radioactive charger used by Wiedensohler et al. (1994). The model allows the simultaneous determination of the N_it-product and the ion and particle losses (due to both electrical and diffusional effects), through a fit of experimental results for charge distribution fractions. The N_it-product represents a key charging parameter, which allows one to calculate other variables. The electric losses are a consequence of the assumption of an electric field in the charging zone, in both the radial and axial directions. Additional measurements of current, electric field or losses are not necessary.

To test the validity of the model, it is applied to a previously developed unipolar corona charger as shown in Fig. 1 (Domat et al., 2014). The device has separated ion generation and particle charging zones, and a sheath flow which transport the ions into the charging region. Its charging characteristics were obtained in experiments with monodisperse particles in the size range of 6–60 nm, number concentrations below 10^5 cm^{-3} and flow rates of 0.5 lpm for the ion flow and 1.5 lpm for the aerosol flow. The electrode consists of a needle mounted on a micrometer allowing one to adjust the distance and thereby varying the N_it-product in the charging zone.

Charged particles experience electrostatic forces in the charging region, since there the ions generate a space charge. Therefore, some percentage of particles will migrate to the walls and get lost there. For ultrafine particle sizes below 20 nm, the probability of charging is lower than for larger diameters, and the fraction of multiply charged particles is very low. Moreover, their losses by diffusion to the walls will be large. Ion concentration varies from the ionization region to the tube, due to the diffusional and electrostatic losses and, when the ion and particle concentrations are comparable, the attachment to particles leads to ion scavenging.

Therefore, a precise estimation of the ion concentration is needed, taking into account the ion and particle losses. An extension of the Fuchs model is presented, and the mean value of the N_it-product in the charging region is obtained. It leads to an improved fitting of the experimentally determined mean charge per particle of the test charger, estimating the amount of ion and particle losses independently.

2. Basic theoretical model

The basic theory for particle charging was developed by Fuchs (1964) in his well known theory of the limiting sphere. Combined with the birth-and-death model, this theory gives a set of differential equations that determine the charge distribution given the initial conditions.

The evolution of a charge distribution by diffusion charging of monodisperse particles is usually approximated by the birth-and-death model given in Boisdron & Brock (1970). In this theory, the solution is given by a set of infinite difference-differential equation (DDE), a two-variable system consisting of a coupled ordinary differential and recurrence equations.