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Flow driven transmission of charged particles against an axial field in antistatic tubes at the sample outlet of a Differential Mobility Analyzer

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ABSTRACT

Electrophoretic losses at the outlet of Differential Mobility Analyzers result from the need to transport the aerosol from the high voltage V_{Bias} typically applied to the inner electrode, to the ground potential at which a particle detector is usually connected. Here we examine the sample transmission efficiency η for mobility-selected ions brought to ground through a commercial Static Dissipative Polyurethane tube. $\eta(V_{Bias})$ is defined as the ratio of the ion current transmitted through the tube with bias voltage V_{Bias} over that transmitted when $V_{Bias}=0$. We find η values close to unity under common DMA operational conditions. η is measured also under adverse fields strong enough for all charged particles to be lost, with a sample transmission efficiency comparable to that expected for a uniform velocity profile within the tube. Outlet tube Reynolds numbers are examined in the range $446 < Re < 4460$, with an increased transmission associated to decreasing Re. The sample transmission efficiency is close to ideal, but geometrical non-idealities are apparent from small decreases in transmission under favorable bias voltages.

1. Introduction

Many scientific instruments, including Differential Mobility Analyzers (DMAs), apply large voltage differences between their inlet and outlet ports. Safe operation then requires transporting the particles against a strong electric field from the high voltage at the inlet or outlet into a grounded region where the sample may be introduced or extracted. For example, DMAs classifying positively charged particles often bias the inner electrode to negative voltages of 10 kV or more. Yet, due to the small mobility Z typical of aerosol particles, the adverse electrophoretic velocities are often considerably smaller than the flow velocities lifting the particles back to ground (For precision's sake, an *adverse electric field* denotes a situation where the mean axial electrophoretic speed opposes the mean flow speed). In such cases, the outlet transmission may be of order unity without careful selection of an outlet insulating material. However, when $\sim$1 nm particles are selected with high resolving power, relatively high electrophoretic velocities are involved, with substantial outlet losses sometimes leading to zero transmission. This difficulty is particularly acute in high resolution DMAs developed over recent years. Three problems arising from the use of insulating outlet tubes must be distinguished. First, any charge initially deposited by diffusion or electrophoresis on an insulating surface, quickly builds up electrostatic fields strong enough to lead to precipitation of other charged particles into electrodes near the insulator surfaces. This first difficulty is substantially alleviated by an antistatic outlet tube, because its finite electrical conductivity quickly removes any deposited surface charge. A second problem surviving even when using antistatic insulator outlet tubes is associated with the net electric field created by the voltage

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difference between the entry and the exit of the outlet tube. Under the most favorable conditions this field may be strictly along the tube axis everywhere except near the tube inlet, and may be compensated by the axial fluid flow. However, any slight geometric imperfection results in radial fields (uncompensated by the flow field) and electrophoretic losses. Finally, even in a perfectly symmetric situation, if the maximal axial fluid velocity along the tube is smaller than the opposed axial electrophoretic speed, the transmission will be zero.

In past work with high-resolution nanoDMAs, we and others had relied on a commercial *static removing plastic* identified by one of the authors (M.A.): TECAFORM SD, commercialized by Esinger. Kangasluoma et al. (2016) have reported the global transmission of a Herrmann DMA with the Tecaform outlet, though without separating outlet electrophoretic losses from other losses. In our own use of a Tecaform outlet for the halfmini DMA, good outlet transmission was often found. However, cases of low transmission occasionally arose in a given DMA following disassembly, due to accidental poor contact between the antistatic tube and the metal electrodes on either of its two ends. Other suspected sources of variation in transmission were lack of electrical uniformity of the antistatic material, or an imperfect symmetry of the antistatic tube (fabricated from a rod), both of which would produce radial fields inside the tube. The use of a related material for a comparable purpose has been reported by Maisser, Barmpounis, Attoui, Biskos, and Schmidt-Ott (2015). Franchin et al. (2015) have achieved improved transmission by creating the desired axial uniform field with a series of stacked rings.

Recently, Bezantakos et al. (2015) have described an inexpensive device for low-resolution aerosol classification, relying also on a commercial antistatic plastic (Static Dissipative Polyurethane tube from FreelinWade). Interestingly, this polyurethane material is sold as a tube rather than a rod. Furthermore, comparison between the actual and expected charged particle transmission of this tube against an axial field (Tammet, 2015) suggests that its geometric and electrical characteristics are close to ideal. Additionally, the material is rubber-like, whence cutting the tube length slightly longer than the distance between the high voltage and grounded electrodes it joins ensures excellent electrical contact on both ends. Accordingly, it seemed to us that this polyurethane tube might provide a more reliable and convenient solution to the DMA outlet problem than those previously tried. The present report will show that this is indeed the case.

2. Experimental

The transmission measurements are made by introducing a fixed concentration of mobility-selected ions carried by a fixed sample flow rate q_o at the inlet of a static dissipative tube, while measuring the ion current transmitted to the tube outlet as a function of the voltage difference V_{Bias} across the tube (Fig. 1). The tube was 85A Static Dissipative Polyurethane (FreelinWade, Oregon), with 1/4″ outer diameter and 1/8″ inner diameter (ID). The transmitted ion current was measured by a Faraday cage electrometer (transimpedance of 2.7 V/pA) connected immediately downstream the antistatic tube. No corrections were made for ion losses. The transmission efficiency reported is simply defined as the ion current measured at the electrometer at voltage difference V_{Bias} over that at $V_{Bias}=0$:

$$\eta(V_{Bias}) = I(V_{Bias})/I(0). \tag{1}$$

The sample ions were produced in the interior of a cylindrical tube with approximate diameter and length of 1″, coated internally with 10 mCi of Ni-63. This radioactive source of low energy beta particles is similar to the smaller source described by Fernandez de la Mora (2015), though has a substantially higher internal volume and twice the activity. It was selected over an electrospray due to the high stability of the ion signal over long periods, an important feature to correctly determine ion transmission based on Eq. (1). Although the ion composition was unknown, the positive ions generated by the radioactive source were seen through repeated measurement of their mobility spectra to remain constant in intensity as well as in mobility over long time periods. This constancy however, required the use of dry and clean bottled air (or nitrogen), as well as Teflon tubes in the path from the gas tank to the antistatic tube. The ions were carried by a flow rate q_i of clean air from the source into a high resolution DMA (the halfmini DMA of Fernández de la Mora and Kozlowski (2013)), where several among the ions produced by the source were size-selected producing well defined peaks. The rubber-like anstistatic tube was kept straight by being inserted inside a PEEK tube 7.77 cm in length, while fitting tightly inside its 1/4″ inner diameter. Prior to being pressed in place, the antistatic tube protruded by about 0.2 mm on both ends of the PEEK tube. The PEEK-antistatic assembly was introduced in the axis region of the DMA and pressed tightly by an external nut such that the upstream end of the antistatic tube was in good electrical contact with the inner electrode of the DMA, while its downstream side was in good electrical contact with a metallic outlet piece carrying the monomobile sample outlet of the DMA into the electrometer. This setup is in fact part of the DMA itself. Under normal DMA operation, as well as in all the experiments described here, the outlet piece is grounded via physical contact with the grounded electrometer. Under normal DMA operation the external DMA electrode is also grounded, while the bullet-shaped inner electrode is kept at a high negative voltage. For the experiments performed here we needed to control the inner electrode potential V_{Bias} as the main variable of the problem, such that the ions traveling through the antistatic tube would do so under a controlled adverse (negative V_{Bias}) axial electric field. We also needed to control the classification voltage V_{DMA}, so as to extract an ion of fixed electrical mobility Z. As a result the outer electrode of the DMA could not be grounded but needed rather to be at a voltage $V_{DMA}+V_{Bias}$ (Warning – this mode of operation involves a serious risk of electrocution, and should never be attempted except with extreme care.).