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Very Long DMA for the Generation of the Calibration Aerosols in Particle Diameter Range up to 10 μm by Electrical Separation

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ABSTRACT

For the generation of the quasi-monodispersed standard (calibration) aerosols, the electrical separation of particles from the aerosol with wide size spectrum can be used in quite a wide particle diameter range, from some nanometers up to approximately 10 micrometers. A solution to the problem of multiple elementary charges on the particles, degrading the quality of the separated aerosol in the range of large particles, was proposed in a separate paper. In this paper, a unique very long DMA for the separation of such large particles is described, together with a technology for its manufacturing. Effects of some possible non-ideal properties of the DMA, arising from the manufacturing techniques used, are investigated both theoretically and experimentally; no significant distortions of the DMA transfer function were found. A new method for the experimental determination of the transfer function of the DMA, using Microsphere Size Standards (highly monodisperse polystyrene aerosols) is described. It was confirmed, that electric wind can be a distortion factor of the DMA transfer function and the continuous tracking of it, when separating standard aerosols, is necessary. Effect of gravity on the DMA transfer function is also discussed.

Keywords: DMA; Electrical separation; Calibration; Transfer function.

INTRODUCTION

For the experimental calibration of the aerosol spectrometers, the quasimonodisperse standard aerosols (calibration aerosols) can be generated by various methods, among which the electrical separation of particles from the polydisperse aerosol (separable aerosol) is one of the most popular ones. The method was at first developed by Liu and Pui (1974) for the calibration of the condensation nuclei counters. Here, in an ideal case at least a part of the particles of the separable aerosol must be electrically charged, whereby their charges must be equal, independent from their diameter d. If a narrow fraction of particles according to their electrical mobility is separated from the separable aerosol, the separated particles form a narrow fraction according to their size (diameter d) as well. The requirement of the particle equal charges is satisfied for small particles (d < 40 nm) by bipolar stationary charging, where the probability of more than one electron charge on a particle is negligible. For larger particles, the multiple charges on some fraction of the aerosol particles are unavoidable, and quasimonomobile calibration aerosol, as obtained by separation according to particle electrical mobility (as a rule, in a Hewitt-type differential mobility analyzer (DMA) (Hewitt, 1957)), has asymmetric or even multimodal size spectrum. The reason for this is in the existence of multiply charged larger particles, having the same mobility as the singly charged "major" particles. With the increasing particle size, the distortions of the size spectrum of calibration aerosol also increase. The problem of multiple charges can partly be solved, if particles are separated from the low-mobility "tail" of the mobility distribution of the separable aerosol, but some low percent of multiply charged particles is unavoidable in the calibration aerosol, and the particle concentration will be quite low. Therefore, electrical separation has not been used for the generation of calibration aerosol with the mean particle diameter of d > 0.5 μm.

At present, a method exists for the preparation of separable aerosol with definitely singly charged particles up to the particle mean diameter $d_m \approx 5$ μm (Uin *et al.*, 2009), and the application of the unique Very Long DMA, developed and built at the Air Electricity Laboratory of the University of Tartu already in 1980 (Peil and Tamm, 1984), has became relevant, e.g. for the calibration of the wide range Electrical Aerosol Spectrometer (EAS) (Tammet, 1980; Mirme *et al.*, 1981; Tammet 1992; Mirme, 1994; Tammet *et al.*, 2002). In comparison to the other popular method for the standard aerosol generation, the atomization of the polystyrene particle size standards, the electrical

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separation has some essential advantages: higher particle number concentration of separated (standard) aerosol, ability to choose any particle size, lack of the "empty" satellite particles and lack of multiply charged particles (when using the method described in (Uin *et al.*, 2009)).

ELECTRICAL SEPARATOR OF THE AEROSOL PARTICLES – DMA

DMA is a second order aspiration capacitor with the divided input and output air flows (Tammet, 1970). Schematic diagram of the Hewitt type DMA is depicted in Fig. 1. The outer electrode of the cylindrical capacitor has an annular slit for input of the separable aerosol with flow rate Φ_2. Between the outer and inner electrodes there are produced: a laminar flow of the filtered sheath air (flow rate Φ_1), and a radial electric field by applying voltage between the electrodes. Charged particles, entering through the input slit, drift towards the inner electrode, their radial drift velocity being proportional to their electrical mobility. Particles in some narrow mobility interval move to the output slit in the inner electrode and are sucked out together with the thin layer of the sheath air near the inner electrode (flow rate Φ_3), forming the calibration aerosol.

Dashed lines in Fig. 1 are the axial sections from the four limiting surfaces formed by the trajectories of the particles with limiting mobilities k_i:

$$k_i = \frac{\varepsilon_0 \Phi^i}{CU} \tag{1}$$

These limiting surfaces are tangential to the borders of input and output slits. Here U is the voltage between the capacitor electrodes, C is the capacitor's active capacitance (the capacitance of the part of the capacitor from the input slit to output slit), ε_0 is the electric constant and Φ^i denotes the flow rate of the air (aerosol) flow passed through the limiting surface under consideration (e.g. $\Phi^1 = \Phi_1 + \Phi_2 - \Phi_3$). The shown design of the DMA enables to calculate C using a simple formula for a part of a definite length of the infinitely long capacitor, as both electrodes have equipotential extensions of the same diameter for both ends of the active part of the capacitor.

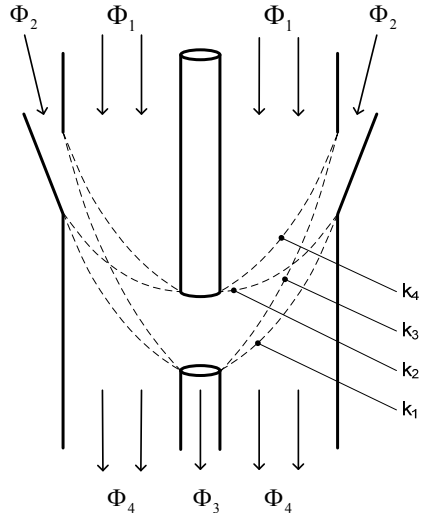

Fig. 1. Working principle of the Hewitt-type DMA.

The main characteristic of the separator is the particle size spectrum of its output aerosol. In case of lack of the interaction between particles in the DMA, the density function $\varphi(k)$ of the particle mobility number spectrum of the calibration aerosol is proportional to the corresponding density function $f(k)$ of the separable aerosol:

$$\phi(k) = H(k)\, f(k) \tag{2}$$

$H(k)$ is the separator's dimensionless transfer function, describing physical processes in the DMA. In case of ideal geometry and exactly laminar and uniform flows, which are uniformly distributed over the perimeter of the annular slit between the electrodes, and choosing $\Phi_2 = \Phi_3$, $H(k)$ has a form of isosceles triangle with the vertexes k_3 and k_2 on the k-axis and the height 1 over the point $k_1 = k_4$:

$$H(k) = \begin{cases} 0 & k < k_3 \\ \left(\dfrac{k}{k_1} - 1\right)\dfrac{\Phi_1}{\Phi_3} + 1 & k_3 < k < k_1 \\ 1 & k = k_1 \\ \left(1 - \dfrac{k}{k_1}\right)\dfrac{\Phi_1}{\Phi_3} + 1 & k_1 < k < k_2 \\ 0 & k > k_2 \end{cases} \tag{3}$$

Small deflections from ideal conditions as well as the diffusion of the particles (being substantial by small particles) distort the form of $H(k)$ – it becomes a bell-form; greater deflections create asymmetry of the bell or even bimodal shape of $H(k)$. The simplest derivation of Eq. (1) and Eq. (3) was made by Hoppel (1978) on the basis of Tammet's general theory of the aspiration mobility analyzers (Tammet, 1970).

In the case of large particles, when the particle settling velocity due to gravity is comparable with its drift velocity in the electric field of the capacitor, the gravity effect must be taken into account. For the vertical cylindrical DMA Eq. (1) can then be modified:

$$k_i^* = \frac{\varepsilon_0 (\Phi^i + \Phi')}{CU} \tag{4}$$

where Φ' is the complementary pseudo-flow rate, reflecting the gravitational flux of particles through the annular cross-section of the inter-electrode volume:

$$\Phi' = v_g \pi (r_2^2 - r_1^2) = \frac{\pi \rho g d_p^{\,2} \Gamma}{18\eta} (r_2^2 - r_1^2) \tag{5}$$

Here v_g is the settling velocity of the particle with

diameter d_p, ρ is the particle matter density, η is the dynamic viscosity of the air, g is the gravity acceleration, Γ is the slip correction factor and r_2 and r_1 are the radii of the outer and inner electrodes of the cylindrical DMA. In case of a triangular form of the transfer function (i.e. $\Phi_2 = \Phi_3$), $\Phi^1 = \Phi^4 = \Phi_1$ and

$$k_1^* = k_4^* = \frac{\varepsilon_0(\Phi_1 + \Phi')}{CU} \tag{6}$$

As it is seen, now the limiting mobilities are not uniquely determined by the separator's parameters of the structure (C) and regime (Φ^i, U), but depend also on the diameter and density of the charged particles. Although the general form of the transfer function of the DMA remains the same (Eq. (3)), the consideration of gravity shifts the triangle along the k-axis.

For the simplification of the computations, Eq. (3) can be rewritten as follows (Stolzenburg, 1988):

$$H(k) = \frac{\Phi_1}{2\Phi_3}\left[\left|\frac{k}{k_1} - 1 - \frac{\Phi_3}{\Phi_1}\right| + \left|\frac{k}{k_1} - 1 + \frac{\Phi_3}{\Phi_1}\right| - 2\left|\frac{k}{k_1} - 1\right|\right] \tag{7}$$

Eqs. (4–6) as well as the statement about the shift of the triangle-form transfer function along the k-axis by considering gravity, can be obtained from the results of the rather complicated approach of the gravity-affected DMA, made by Le Bronec *et al.* (1999), but a simpler and more direct derivation can be made for a vertical DMA, using Hoppel's-Tammet's method (Tammet, 1970; Hoppel, 1978). The details of this derivation will be presented as a part of a future article.

ASSESSMENT OF THE STRUCTURAL AND REGIME PARAMETERS OF THE DMA FOR THE SEPARATION OF PARTICLES WITH DIAMETER UP TO 10 μm

Until now, the only possibility to satisfy the requirement for the homogeneity of particle charges of the separable aerosol is to use the singly charged particles from the aerosol with the stationary charge distribution. From the Millikan formula, it can be seen that the electrical mobilities of the singly charged large particles ($d \geq 1$ μm) are quite low: around 10^{-10} m^2/V·s for 10 μm particles, which is 10 times lower than the mobility of 1 μm particles. Of course, using the stationary charge distribution with large aerosol particles, it is practically impossible to avoid multiply charged particles in the output aerosol, which reduce the quality of the calibration aerosol. A new method for preparing the separable aerosol, solving the problem of multiple charges for large particles was developed by the authors of the present paper (Uin *et al.*, 2009) and is now used in a special instrument (Yli-Ojanperä *et al.*, 2010).

For successful electrical separation of large aerosol particles (up to particle diameter 10 μm), a special DMA must be designed. The minimal value of the limiting mobility k_1^* (Eq. (6)) has to be 9.5×10^{-11} m^2/V·s. Next it is attempted to assess the values of the quantities in Eq. (6) for achieving such a limiting mobility.

From Eq. (6) it can be seen that to achieve low values of k_1^* both the capacity C of the DMA and the voltage U between its cylindrical electrodes must have values as high as possible, and the flow rate Φ_1 must be as low as possible. To avoid electrical breakthroughs, it is advisable to avoid voltages over 10 kV. The settling velocity of 10 μm particles is $v_g \approx 3$ mm/s; to avoid too long measurement cycle times when scanning over the particle size spectrum of the separable aerosol (which is required for choosing the correct voltage for the separation of the particles of the needed mean diameter), the mean linear speed $\bar{v}$ of the air flow between the DMA electrodes should be substantially higher than v_g, thus $\bar{v} \geq 5v_g$ is chosen. Choosing for ratio Φ_2/Φ_1 a common value 0.1, it can be written:

$$\begin{aligned}\Phi_1 + \Phi' &= (0.91\bar{v} + v_g)\,\pi\,(r_2^2 - r_1^2) = 5.6\,\pi\, v_g\,(r_2^2 - r_1^2) \\ &\approx 6\pi\, v_g\,(r_2^2 - r_1^2)\end{aligned} \tag{8}$$

Using the formula for the capacitance of a section with length L of an infinitely long cylindrical capacitor, it is obtained:

$$k_1^* = \frac{3\ln(r_2/r_1)}{LU} v_g\,(r_2^2 - r_1^2) \tag{9}$$

and, using the above-mentioned numeric values:

$$\frac{(r_2^2 - r_1^2)\ln(r_2/r_1)}{L} = \frac{k_1^* U}{3v_g} = 1.05 \times 10^{-4}\,\text{m} \tag{10}$$

Geometric parameters r_1, r_2 and L have to be chosen so that the condition given by Eq. (10) is fulfilled and the mechanical details with the chosen dimensions are technically realizable (in our particular conditions). An additional requirement is as small as possible mass of the DMA. So the technology of the flow turning from a pure (soft) aluminium sheet was chosen, the maximum realizable dimensions of the cylinder being: the diameter of approximately 100 mm and the length not more than 150 mm. Therefore, $r_2 = 50$ mm; for the maximum capacitance C , r_1 ($< r_2$) must be chosen as large as possible, but with the decreasing of the width of the annular slit between the cylinders, the uncertainty of the limiting mobility of the DMA caused by the technologically unavoidable non-coaxiality of the cylinders increases quite sharply. Therefore $r_1 \approx 42$ mm was chosen. Then from Eq. (10) $L \approx 1200$ mm is obtained, and the active capacitance of the DMA $C \approx$ 390 pF, the sheath flow rate for the separation of 10 μm diameter particles $\Phi_1 \approx 2$ L/min.

THE VERY LONG DMA FOR THE SEPARATION OF LARGE AEROSOL PARTICLES

For the purposes of experimental calibration of the wide-range electrical aerosol spectrometer EAS (see section 1), the Very Long DMA, satisfying the conditions described in section 3, was developed and built in 1980 at the Air Electricity Laboratory of the Tartu State University (now Laboratory of Environmental Physics of the Institute of Physics of the University of Tartu). A short description of this DMA as a separator of aerosol particles with diameter up to 2 μm was first published in 1984 (Peil, Tamm, 1984).

The separator of aerosol particles – the Very Long DMA – is depicted in Fig. 2. It represents a cylindrical capacitor whose outer electrode (radius r_2) and inner electrode (radius r_1) are composed of cylindrical sections produced by flow turning (a special technology for fabrication of cylindrical-symmetric details from a flat metal piece (plate)) and joined by epoxy glue. The separable aerosol flows through three holes, uniformly positioned on the perimeter, into the space between two cones and, after the suppression of the turbulence, enters through a slit in the outer electrode into the active zone of the DMA with the flow rate Φ_2. The filtered sheath air (flow rate Φ_1) enters through 35 small holes in the input tube and penetrates through the space with a tapering annular cross section (for suppression of turbulence) into the active zone of the DMA. Separated particles (calibration aerosol, flow rate Φ_3) are sucked out through a slit in the inner electrode and 12 uniformly positioned holes on the perimeter of the support part of the inner electrode. Excess air (flow rate Φ_4) is sucked out through a slit and 3 holes in the base of the DMA. Three output holes (as well as three input holes for the separable aerosol) should assure the uniformity of the flows over the perimeter. The width of the input and output slits is 2 mm and 1 mm, accordingly. Design of the input of the DMA is to some extent similar to the so-called Vienna DMA one (e.g., Winklmayr, 1987), although the authors were not familiar with the work of the Vienna group. Such a solution seems to be optimal in some sense.

A special feature of the described DMA is a possibility to check visually the laminarity of the flows. Through the window on the top of the DMA, it is possible to observe, by means of a special small telescope (telescopic sloop), the unclassified aerosol layer near the outer electrode (the voltage U between the electrodes is zero) or the layers corresponding to the neutral and one-, two- and so on-fold charged particles (U is some kilovolts) just before the

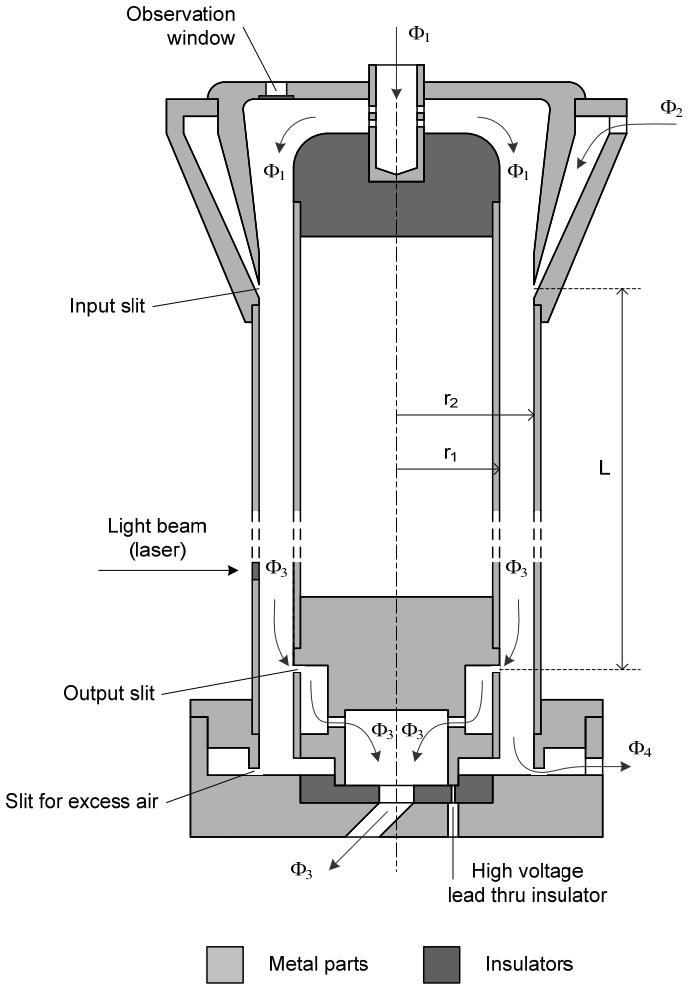

Fig. 2. Long DMA (separator) for large particles (d_p up to 10 μm). Dimensions: r_1 = 42.15 mm, r_2 = 50.0 mm, L = 1200 mm. Active capacitance of the DMA is 390.7 pF.

output slit. Aerosol layers are illuminated through the window in the outer electrode. With a laminar flow the borders of the layers are sharp circles. This arrangement of visual flow-checking enabled to discover the presence of the electric wind in the DMA in case of the classification of charged particles with high number concentrations (Peil, Tamm, 1984). The turbulent electric wind distorts the transfer function of the DMA as evidenced by a "smeared" aerosol distribution (i.e. without clearly separate maxima for differently charged particle fractions) when measurements were done with the electric wind being present. The critical voltage by which the electric wind arises is dependent not only on the charged particles number concentration (volume charge density), but also on the particle size – with the increasing size the critical voltage decreases (by the same volume charge density). Therefore, when the long DMA is used for separating large particles, visual (or with a CCD camera) checking of the laminarity of the flow is essential. Using the traditional method for separating the particles from an aerosol with a stationary charge distribution, where multiply charged particles increase the volume charge density between the electrodes, consideration of the possibility of the electric wind is essential even with particles with d < 500 nm. This phenomenon must also be taken into account when aerosols with high particle concentrations are measured using electrical spectrometers. Dependence of the threshold voltage (electric field strength) for arising of the electric wind in the DMA on the volume charge density between the electrodes of the DMA and on the mean diameter of the particles of a separable (measurable) aerosol needs a special theoretical and experimental study.

Flow rates Φ_i (i = 1, 2, 3, 4) are adjustable, depending on the diameter of separable particles, the required particle concentration and the required width of the particle size spectrum. For the sheath air, a closed loop arrangement is used. The closed loop automatically guarantees equality of the flow rates Φ_1 and Φ_4 (and also Φ_2 and Φ_3). Electric and fiber filters remove the neutral and low-mobility charged particles carried out from the DMA, so that the sheath air is clean from particles before re-entering the DMA. A flow meter and a valve are used for the adjustment of the sheath air flow rate. Experimental study using the above-mentioned visual-optical method showed that the air flows in the DMA are laminar up to at least 25 L/min flow rate of the sheath air. By Φ_1 = 33 L/min, a remarkable turbidity of the borders of the aerosol layers in the DMA was seen, which indicates the existence of some turbulence.

Voltage between electrodes is adjustable, along with its polarity. Voltages up to U = 10 kV are allowable; by 11 kV electrical breakthroughs sometimes arise. Taking this into account, the maximum sheath air flow rate for the separation of the particles with the given diameter (Table 1) can be calculated from Eq. (6) (using the mobility of the singly charged particles). Maximizing the sheath air flow rate, while keeping the ratio Φ_2/Φ_1 constant, is useful for obtaining a higher particle concentration of the calibration aerosol. For the largest particles (d = 10 μm, gravitational settling velocity $v_g \approx 3$ mm/s), the maximal value of Φ_1 = 2.1 L/min gives the mean velocity of air flow between the cylindrical electrodes $\overline{u} \approx 15$ mm/s. Comparison of these two velocities clearly demonstrates the importance of considering the effect of gravity in a DMA when such large particles are used.

As said in section 3, with ideal conditions – the air flows fully laminar and exactly uniformly distributed over the perimeter, the exactly coaxial ideally cylindrical electrodes of the DMA and non-diffusive particles – the transfer function of the separator has a triangular form. The relative half-width of it at the half-height (analogous to σ of the Gaussian curve) is determined by the ratio of air flow rates:

$$\delta k^* = \frac{k_2^* - k_3^*}{2k_1^*} = \frac{\Phi_2}{2(\Phi_1 + \Phi')} \approx \frac{\Phi_2}{2\Phi_1}. \quad (11)$$

The commonly used value for Φ_2/Φ_1 = 0.1 gives δk^* = 0.05, which is considered satisfactory for the calibration aerosols. For large particles, the effect of gravity makes the transfer function narrower.

Of course, the above-described technology of manufacturing the electrodes of the DMA could not ensure the ideal geometry of the DMA, also the distribution of aerosol flow on the perimeter of the annular slit may not be exactly uniform. Therefore, the real transfer function could be different from ideal.

INVESTIGATION OF THE DMA TRANSFER FUNCTION

Theoretical Calculations

Series of calculations were made to investigate the effects of imperfections in the DMA construction on the DMA transfer function. Namely, the effect of non-concentricity

Table 1. Maximum sheath air flow rate for the separation of singly charged DOP (dioctylphtalate, ρ = 983 kg/m^3) particles by U = 10 kV.

Particle diameter d_p (μm)	Limiting mobility of the DMA $k_1^* \times 10^{10}$ (m^2/V·s)	Maximum sheath air flow rate Φ_1 (L/min)
1.0	10.10	29.0
2.0	5.09	13.5
4.0	2.44	6.4
6.0	1.61	4.1
8.0	1.20	2.9
10.0	0.95	2.1

of the DMA cylindrical electrodes was examined. An analytical approach to solve this problem was made by Knutson (1971). Here a numerical method is attempted using a simple model of the Very Long DMA.

To calculate the DMA transfer function, the space between the electrodes was divided into 1000 vertical sections (segments) so that the cross section of the outer electrode (also the inner one, if they are concentric) was comprised of sectors with equal central angles $d\phi$ (Fig. 3). The overall transfer function was calculated as an average of transfer functions of these individual sections. The limiting mobilities and transfer functions were calculated according to Eq. (3) and Eq. (7). This was possible because according to Tammet (1970), the general theory developed for the cylindrical aspiration capacitor is applicable to a sector of the cylindrical capacitor, as well as to the parallel-plate capacitor. The volume flow rates in the sections were taken to be proportional to the area A of its cross section, i.e. the profile of the air flow was considered to be uniform and not dependent on the distance between the electrodes (the model of the ideal fluid was used). For finding the capacitance of the section, the corresponding parts of the inner and outer electrode were taken to form a parallel-plate capacitor with the width of the plate being determined by the part of the inner electrode.

The calculations were made with specific working parameters of the above-described Very Long DMA (the construction parameters were those given in section 4): aerosol flow 30 l/h (divided between the three inlets), sheath air flow 500 l/h, the DMA voltage 1000 V. The distance between the axes of the two cylinders was varied so that Δr = 0, 0.2, …, 1.4 mm.

The results of the calculations, modelling the shift of the electrodes, are presented in Fig. 4. As it can be seen, without the shift between the axes of the cylinders, the transfer function has the expected triangular shape. With increasing Δr, however, the transfer function gets wider and lower until actually more than one maxima appear. A significant decrease in the transfer function height can already be seen with shifts between the cylinder axes below 1 mm. Analogous distortions of the transfer function could also appear in the case of a slightly curved central electrode, which can exist due to the above-described production technology of the Very Long DMA.

Theoretical assessment of the DMA transfer function was performed using the model of ideal fluid, i.e. the velocity profile between the cylindrical electrodes of the DMA was assumed uniform. Partial flow rates for imaginary vertical sectors of the space between the non-concentric cylindrical electrodes were assumed to differ

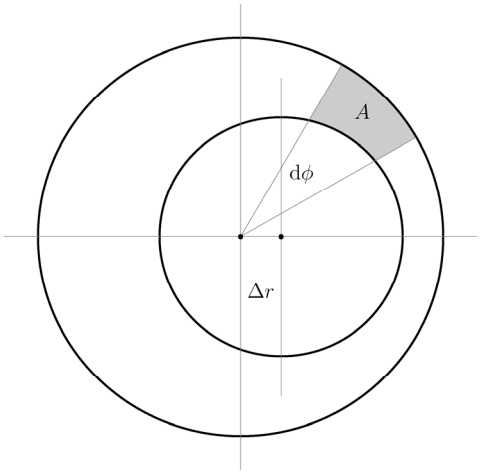

Fig. 3. Cross-section of the cylindrical DMA electrodes. The outer electrode is divided into sectors with the central angle $d\phi$ forming a vertical section (segment) between the electrodes with a cross section area A. The axes of the two cylinders are shifted by Δr.

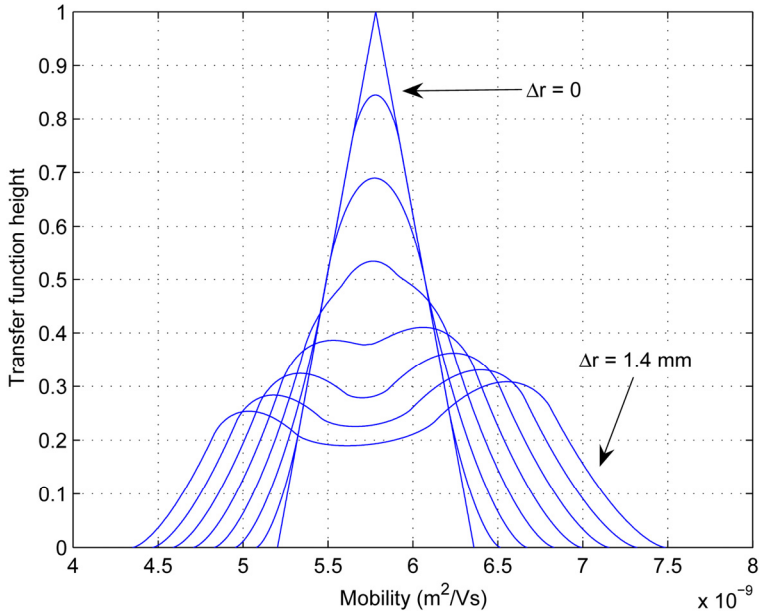

Fig. 4. DMA transfer function in case of different distances Δr = 0, 0.2, …, 1.4 mm between the cylinder axes.

from each other only due to different cross section areas of the sectors. In case of real (viscous) fluid, the difference in mean velocities and, therefore, also in partial flow rates between the sectors of different cross section areas is higher than in case of the ideal fluid model. Therefore, the general nature of distortions in the transfer function should be the same in both cases. The only difference should be in the magnitude, with the case of the real fluid having larger distortions. The more exact theoretical investigation of the distortions of the DMA transfer function needs a more thorough investigation; here, only the above-described first assessment of the distortion caused by non-concentricity of cylindrical electrodes is presented, and compared with experimental results.

Experimentally Determined Transfer Function

The transfer function of the Very Long DMA was also measured experimentally to check whether any previously described distortions could be observed. Usually a tandem-DMA setup is used (Birmili *et al.,* 1997; Stratmann *et al.*, 1997; Uin *et al.*, 2006) for determining the DMA transfer function. Here, however, this method is not suitable, as in addition to the DMA under investigation, it requires the presence of another, identical or at least similarly capable DMA. As the Very Long DMA is rather unique, this is not possible. Another way for determining the DMA transfer function, which does not require multiple DMAs, is to measure a highly monodisperse aerosol. Considering the definition of the transfer function (Eq. (2)), the particle concentration n at the output of a DMA can be described by:

$$n(k_1) = \int H(k, k_1) f(k) \, \mathrm{d}k \tag{12}$$

where k_1 is the midpoint mobility of the DMA transfer function. It can be seen that when scanning over the aerosol distribution with a DMA, the measurement result (particle number concentration on the output of the DMA) is a convolution between the aerosol distribution and the DMA transfer function. If the aerosol distribution is very narrow (much narrower than the DMA transfer function), then the measurement result can be approximated as a convolution between the transfer function and a delta function, which is equal to the transfer function itself (change in the absolute width of the transfer function, when shifting the voltage of the DMA during scanning, is small enough to be ignored).

To use this method, a suspension of polystyrene microspheres with the mean diameter of 1 (0.994) μm and the standard deviation of 0.010 μm was atomized to produce a monodisperse test aerosol. The obtained aerosol was then dried in a silica gel drier and neutralized using a ^{239}Pu neutralizer. As stated above, the electric wind can be a problem. In this case the cause for the electric wind is the presence of small charged droplets of the added stabilizer in the polysterene suspension. To remove their effect, the aerosol was led through an electric filter, which removes these small charged particles. Finally, the dependence of the DMA output signal (particle number concentration) on the voltage applied to it was measured using the Very Long DMA and a CPC. A triangular function (Stolzenburg, 1988) was fitted to the measured distribution of the output concentration for singly charged particles (singly and multiply charged particles in the measured distribution were easily distinguished, i.e. there was no overlapping) and the relative half-width β of the function was obtained (Fig. 5). Here, only the half-width of the transfer function was examined and the height (and area) of the transfer function were not investigated, as the total aerosol concentration is, in this case, practically impossible to determine. The measurement results gave β = 0.17 (ideal value, determined by the DMA airflows, would be 0.1).

There are several possible causes for the broadening of the transfer function: the non-ideal geometry due to described technology of the fabrication of the cylindrical electrodes or possible not exactly uniform distribution of the flow on the perimeter of the annular slit. Of course, some visually difficult-to-observe trace of turbulence, caused by the electric wind can also broaden the transfer function, but this would also have a strong effect on the transfer function shape. In this case, the non-ideal geometry seems to be the most likely cause. However, as stated above, no significant distortions in the shape of the transfer function of the Very Long DMA are visible.

As stated previously, the height of the DMA transfer function was not investigated, therefore, the vertical axis in Fig. 5 shows the aerosol concentration as measured by the CPC. This is presented to illustrate the relatively low particle concentrations available, which can make the described experiments difficult. Attempts were also made to use aerosols with 7.9 μm mean diameter, as the Very Long DMA is capable of measuring/separating particles with diameter up to 10 μm. However, while the solid content of the 7.9 μm suspension is approximately 10 times higher than that of the 1 μm suspension, the volume of a particle is 10^3 times higher, which gives much lower number concentrations and makes the particle detection/counting even more difficult. It must be noted though, that while performing the actual experiment with larger particles was impossible, there are no strong arguments why the transfer

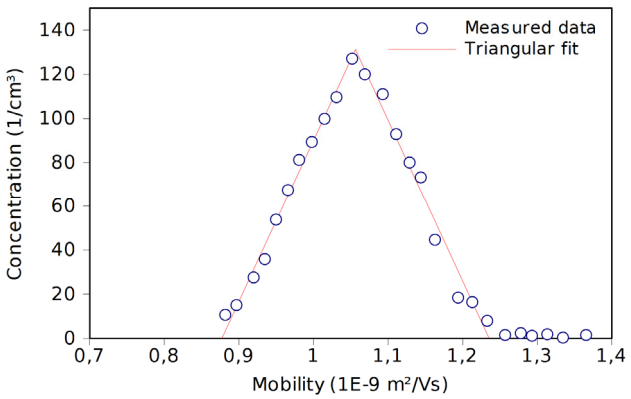

Fig. 5. Experimentally found DMA transfer function and triangular fit (R^2 = 0.990).

function of the Very Long DMA should be different with larger particles. For experimental demonstration of the gravitational shift of the DMA transfer function, the efforts for repeating the above-described experiment with larger particles will be continued.

CONCLUSIONS

For the generation of the standard aerosols for the calibration of aerosol spectrometers with a very wide measurement range according to particle diameter, the electrical separation of the particles from the aerosol with a comparatively wide particle size spectrum seems to be the best method. Design principles of the Very Long DMA for the separation of particles up to the diameter of 10 μm are described. An electrical particle separator, developed and built according to these principles, is presented. The effect of gravity, in case of large particles, on the DMA transfer function, is discussed. Distortion of the DMA transfer function caused by non-concentricity of the DMA cylindrical electrodes is assessed theoretically in the first approximation. A new method for the determination of the DMA transfer function is used utilizing monodisperse polystyrene size standards. No theoretically predicted distortions to the transfer function shape are found. The investigation also confirmed the earlier known statement (Peil and Tamm, 1984), that electric wind can distort the transfer function of the DMA, therefore, when separating large particles, a visual check of the laminarity of the flow was found to be necessary. With the new method available for reliably producing singly charged large particles, the instrument is successfully being used for the calibration of aerosol spectrometers, such as the very new version of the EAS (results of this work are not published yet).

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