Performance of a Miniaturized, Lightweight, and Cost-effective Parallel-Plate Differential Mobility Analyzer

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Abstract Size resolved measurements of aerosol particles are essential for understanding key processes in the atmosphere, and assessing their potential impacts on human health and climate. This has led to an increasing demand for compact and portable, yet cost-effective, instruments for characterizing the atmospheric aerosol.

A commonly employed instrument for sizing aerosol particles in the sub-micrometer range is the Differential Mobility Analyzer (DMA). Commercial DMAs weigh several kilograms, and have a cost higher than 10 kEUR. When employed in aerosol size spectrometers, they attribute a poor time resolution to the system (in the range of several minutes), as they require scanning of their operating conditions. This limits their ability to probe rapidly-changing aerosols caused by certain processes. One way to overcome this limitation is to employ several DMAs operated at fixed conditions (instead of one in which the operating conditions are scanned), but doing so multiplies the weight, the size and the cost of the entire system.

Here we report on the design and testing of a lightweight, miniaturized and cost-effective Parallel-Plate DMA. The weight of this DMA is reduced to less than 1 kg, whereas its manufacturing cost is two orders of magnitude less than that of their commercial counterparts.

Keywords: cost-effective and lightweight instruments, size distribution, new particle formation

1. Introduction

Understanding atmospheric key processes is a requirement for the development of climate models and climate predictions. Currently, climate models, to a large extend rely on assumptions when it comes to the influence of particulate matter on climate developments. Improving aerosol related understanding of climate effects and validating the assumptions implemented in climate modelling requires a tight network of routine (continuous) monitoring stations capable of providing size resolved aerosol measurements (Kulmala et al., 2004).

In addition, it is known that airborne particles can be associated to many adverse health effects in the human populations, which results to an additional need for aerosol monitoring, both indoors and outdoors (Kulmala et al., 2004; Liu and Chen, 2016).

Currently existing limitations in aerosol monitoring come from the associated costs to implement and run measurement stations as well as for the relatively large space required to setup existing commercially available instruments.

The most commonly applied instrument capable of producing reliable continuous data on the aerosol size distribution in the sub-micrometer range and especially in the range where particles get too small for optical measurements is the Differential Mobility Analyzer (DMA; Knutson and Whitby, 1975). DMAs consist of two electrodes between which a potential difference is applied, and a laminar sheath flow. Polydisperse aerosol is introduced with a flow into the classifier without mixing and carrying the particles containing flow downward the instrument. The electric field is forcing the charged polydisperse particles to migrate from one electrode to another. Only particles having sizes within a narrow range pass through the outlet of the classifier and can be subsequently counted in a detector.

One major limitation of DMAs, however, is the time it takes to scan over the entire particle size range to get the full-size distribution of the sampled aerosol. Scanning leads to losses of information and to poor counting statistics at each size channel. In order to avoid the limitation and uncertainties of the Scanning Mobility Particle Sizers (SMPSs), Stolzenburg et al. (2017) introduced the train-DMA setup (i.e., six DMA employing in parallel at six different and fixed voltages with six individual particle counters). This system has been proven to be very useful to overcome the time resolution limitations of classical SMPS system. However, it is a very bulgy and expensive setup and therefore not suitable for wide scale applications.

Existing demands to improve aerosol monitoring has led to the development of lower cost instruments in recent years. The focus has moved towards the development of portable, and cost-effective instruments. Efforts have been made to reduce the weight and the cost of cylindrical DMAs (Barmpounis et al., 2016) with good performance. In addition to cylindrical DMAs, several research studies reported on the development Parallel-Plate-DMAs which carry the advantage of a more compact and simpler design and therefore, even better possibilities for the reduction of size, weight and manufacturing costs (PP-DMAs; Chen, Li and Cheng, 2007; Steer et al., 2014; Liu and Chen, 2016; Chen et al., 2019).

In this work we manufactured a small a PP-DMA and subsequently tested its performance in lab and field experiments. The efforts were carried out with the scope to setup a lightweight cost-efficient DMA-train consisting of at least 3 DMAs operating in parallel for a fast response routine aerosol modelling. Additionally, the method will be further developed in the future to implement it on UAV (unmanned aerial vehicles) aerosol monitoring measurement flights.

2. Experimental

2.1. Design of the PP-DMA

As mentioned above a DMA is an instrument to measure electrical mobility of airborne particles. Electrical mobility can be related to the particle size. The DMA has been established as a very common aerosol instrument and has been described in great detail in a large number of publications (Flagan, 1998). In brief, the basic working principle is that charged airborne particles are introduced with an airflow (aerosol flow) into a larger laminar sheath flow that is established between two (in our case parallel plate) electrodes. The sheath flow and the aerosol do not mix and the aerosol flow remains close to the inlet plate. Between the electrode, however, an electrical field is applied which attracts charged particles of one polarity to deviate from the flow stream lines and move towards the outlet electrode plate. For a specific DMA geometry and a constant sheath flow rate and a specific electrical field (voltage applied) only a narrow fraction of aerosol sizes would exit the instrument through its outlet slit. The near monodisperse particles can then subsequently be measured with a particle counter. When scanning over a number of size channels (different voltages) a size distribution measurement can be recorded.

The characteristic dimensions of our PP-DMA are summarized in Table 1. The insulator was a POM (polyoxymethylene, a thermoplastic with dielectric strength of >50 KV/mm) material and both plates on which the potential difference is applied were made out of aluminum. The inlet and the outlet of the particles were 3D printed parts made out of Resin and their surfaces were coated with a Graphite based spray (N-77 spray graphite). These parts were assisting the particles to be introduced in the classification zone in 30° angle (cf. Figure 1).

Table 1. Characteristic dimensions of the DMA used in this work

Type	Symbol	Description	Value	Unit
PP-DMA	L	Effective length	10.80	cm
	H	Distance between the electrodes	1.35	cm
	W	Width	10	cm

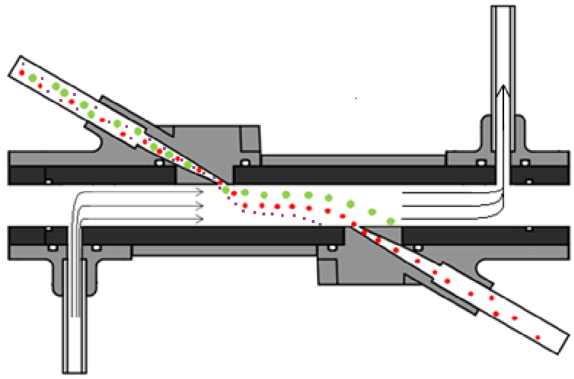

Figure 1. Layout of the Parallel Plate DMA

The weight of the PP-DMA is less than half a kilo, which is less than 10% of the most common commercial instruments. The manufacturing and the cost of the materials are around 80 Euros. The weight, cost and the easy manufacturing process making this instrument very attracting for a wide range of potential applications.

2.2. Characterization of the PP-DMA

2.2.1. Experimental setup

The instrument performance was evaluated by carrying out a tandem DMA experiment which is a standard method for DMA characterization and has been described in great detail elsewhere (Birmili et al., 1997). In a tandem DMA experiment an already characterized DMA is used to generate nearly monodisperse test aerosol that are used for the characterization of the unknown DMA (cf. Figure 2). In our case polydisperse particles of ammonium sulfate (AS) were produced by atomizing a 0.04% w/v AS solution (TSI Model 3076 atomizer). The aerosol flow from the atomizer was passed through a silica gel diffusion drier to remove the water and have polydisperse, dry airborne salt particles in order to bring the aerosol particles in a known charge state the particles were passed through a ^{85}Kr aerosol charger (TSI Model 3077). The radiation source produces an ion cloud by air ionization. The particles passed through the high density ion cloud are charged by diffusion charging. By the time the aerosol flow exits the charger there has been sufficient time to reach charge equilibrium and therefore, the particles are in a known charge state (Boltzmann charge equilibrium) (Fuchs, 1963).

The DMA1 (cf. Figure 1) was a standard commercial DMA (TSI Model 3081). The PP-DMA was characterized for 5 different sizes in the range from 20 to 90 nm. After the first DMA the flow was split into two lines. In the first line the number concentration of the monodisperse particle was recorded by an aerosol electrometer (TSI Model 3068A). The second line led to the PP-DMA for characterization. The PP-DMA (DMA2, cf. Figure 1) was operated in scanning mode over the entire voltage range and the number concentrations were measured by a commercial condensation particle counter (CPC, TSI Model 3022A). A condensation particle counter exposes airborne particles to a defined supersaturated vapor which leads them to grow into optically detectable sizes which are counted by a laser/photodetector configuration.

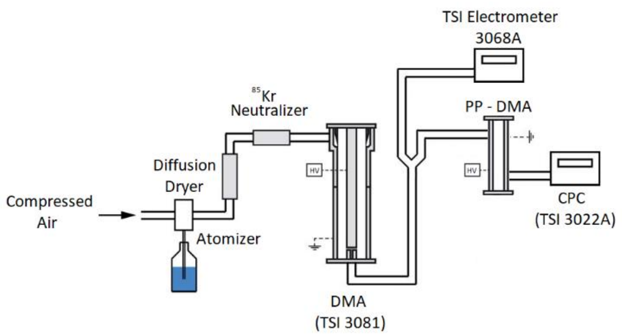

Figure 2. Schematic diagram of the experimental setup

The midpoint particle electrical mobility (Equation 1) corresponding to classified particles according to the operational conditions (voltage and flow rates) and to the characteristic dimensions of the classifier is described as:

$$\boldsymbol{Zp^{*}} = \frac{\boldsymbol{Q_{sh}H}}{\boldsymbol{LWV}}, \quad (\mathbf{1})$$

where Z_p* is the midpoint electrical mobility of classified particles; Q_{sh} is the sheath flow; V is the applied voltage on the PP-DMA; H is the distance between the electrodes; L is the effective length of the classification zone and W is the width of classification zone.

$$\boldsymbol{D_p} = \frac{\boldsymbol{neC_c}}{\boldsymbol{3\pi\eta Zp}}, \quad (2)$$

The calculation from electrical mobility to size has been done using Equation 2, where D_p is the particle diameter, n is the number of elementary charges on the particle, e is the elementary charge, C_c is the slip correction factor, which is a correction factor that accounts for the slip of air molecules around a very small particle, and η is the air viscosity. The slip correction factor is an empirical size dependent parameter taken from literature (Allen and Raabe, 1985). In addition, the resolution and transmission of the instrument were theoretically predicted and experimentally measured in a tandem DMA measurement. More details about the theoretical and experimental procedure can be found in the literature (Santos et al., 2009).

3. Results and discussion

The experiments recorded from scanning the entire voltage range in the second DMA (PP-DMA) are displayed in Figure 4. The applied voltages have been translated into electrical mobility and subsequently into particle diameter. The graph shows the D_p vs. the fraction N_2/N_1. The measurement has been carried out for 5 different diameters. Fig. 3 shows the recorded distributions at 23, 64, and 90 nm. The peaks are well resolved and the peak heights indicates good transmission through the instrument.

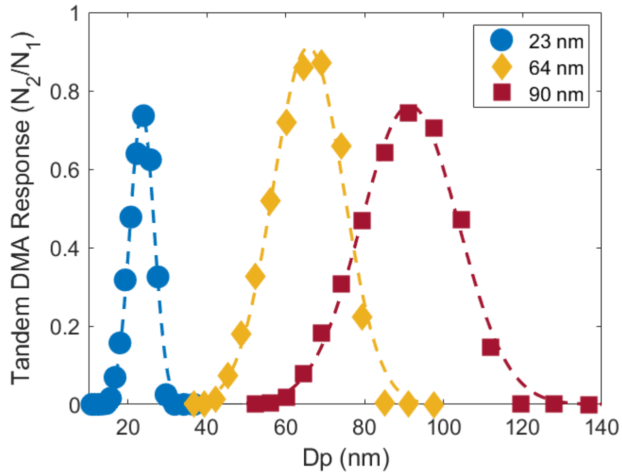

Figure 3. Measured transmission and fitted lognormal distribution, showing the performance of the PP-DMA at 23 nm particles (blue circles), 64 nm particles (yellow diamonds) and 90 nm particles (red squares).

The measurement results were also plotted to show the sizing accuracy, the FWHM of the peak and the transmission height (cf. Fig. 4 and 5). The sizing accuracy has been determined by comparing the voltage of the peak position measured in the PP-DMA to the set diameter in the size selecting DMA1 and the results are plotted in Fig.4. The sizing accuracy is within 5% which is very satisfactory for the targeted application.

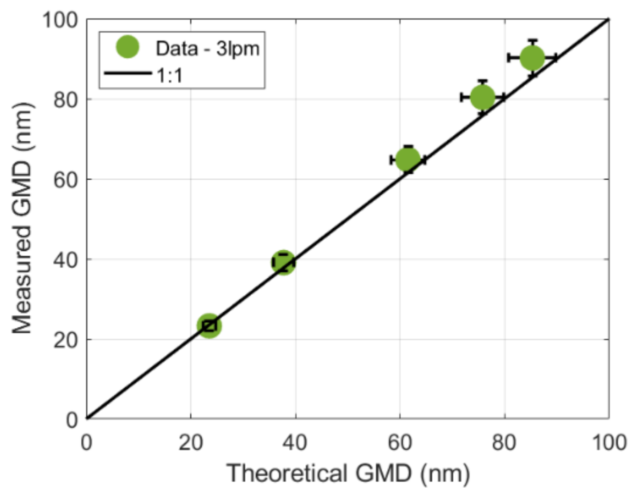

Figure 4. Measured vs. theoretically-predicted geometrical mean diameters (GMD) of the PP-DMA, when operated with sheath to aerosol flow 3/0.3 lpm. The error bars represent a ±5% uncertainty in the sizing.

Additionally, the instrument resolution (full with of half maximum FWHM) and the transmission height were evaluated for each diameter and compared to the theoretically predicted resolution. The results are shown in Fig. 5. It can be seen that the FWHM and the height measured does not show a strong size dependence over the investigated size range. This means that diffusional losses inside the instrument as well as diffusion broadening of the distribution do not play a significant role in the investigated size range, which is in agreement with the theory. The FWHM is about double of the ideally predicted resolution. This can be connected mostly to the cost-efficient manufacturing where the electrodes were not polished before using them which might lead to small imperfections in the surface causing small flow instabilities inside the instrument. Since the requirements for our targeted experimental applications in terms of resolution are fully satisfied with the current performance no further efforts were carried out to improve the instrument in regard to resolution. The peak heights as shown in Fig. 5 a are very close to the theoretically expected value and is therefore very satisfactory for our needs.

Currently, the instrument is being evaluated at a field measurement station where some initial performance evaluation results are expected to be available in the next few months. Depending on the field performances a full DMA train consisting of 3 PP-DMAs will be established for a routine measurement performance evaluation and be operated continuously for a period of several months.

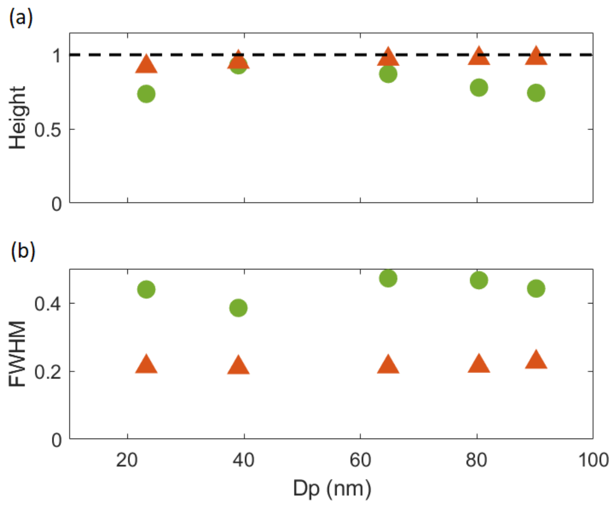

Figure 3. Comparison of height (a), and FWHM (b) of the PP-DMA for the theoretically (orange triangles) and experimental (green circles) results, when operated with aerosol to sheath flow ration 0.3 lpm/3 lpm. The black dashed line in (a) represents the maximum height of the transfer function.

4. Conclusions

The results show that a simple cost-efficient lightweight PP-DMA design shows great potential for its application in field measurements as part of a lightweight DMA train. The performance of the DMA in terms of sizing is within 5% of the theoretical predictions. The instrument shows also very good transmissions throughout the entire size range evaluated. The resolution is about half of what the theory would predict. This is associated to a higher surface roughness of the plates which might lead to local deviation from the laminar flow which allows a wider range of particle sizes to be classified. The resolution of the instrument could be further improved. However, the field tests and the targeted applications do not require high size resolution and the performance of the current prototype fulfills all requirements. Currently, the instrument is tested for its field monitoring capabilities and further prototypes are under construction for setting up a 3 PP-DMA train to establish a lightweight, cost-effective, fast aerosol size distribution monitoring device for routine monitoring applications.

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References

Allen, M. D. and Raabe, O. G. (1985), Slip correction measurements of spherical solid aerosol particles in an improved millikan apparatus, *Aerosol Science and Technology*, **4**, 269–286.

Alsharifi, T. and Chen, D. R. (2018), On the design of miniature parallel-plate differential mobility classifiers, *Journal of Aerosol Science*, **121**, 1–11.

Barmpounis, K. et al. (2016), Lightweight differential mobility analyzers: Toward new and inexpensive manufacturing methods, *Aerosol Science and Technology*, **50**, ii–v.

Birmili, W. et al. (1997), Determination of differential mobility analyzer transfer functions using identical instruments in series, *Aerosol Science and Technology*, **27**, 215–223.

Chen, D. R., Li, W. and Cheng, M. D. (2007), Development of a multiple-stage differential mobility analyzer (MDMA), *Aerosol Science and Technology*, **41**, 217–230.

Chen, M. et al. (2019), Simulation of miniature PDMA for ultrafine-particle measurement, *Atmosphere*, **10**, 1–12.

Flagan, R. C. (1998), History of Electrical Aerosol Measurements, *Aerosol Science and Technology*, **28**, 301–380.

Fuchs, N. A. (1963), On the stationary charge distribution on aerosol particles in a bipolar ionic atmosphere, *Geofisica Pura e Applicata*, **56**, 185–193.

Knutson, E. O. and Whitby, K. T. (1975), Aerosol classification by electric mobility: apparatus, theory, and applications, *Journal of Aerosol Science*, **6**, 443–451.

Kulmala, M. et al. (2004), Formation and growth rates of ultrafine atmospheric particles: A review of observations, *Journal of Aerosol Science*, **35**, 143–176.

Liu, Q. and Chen, D. R. (2016), Experimental evaluation of miniature plate DMAs (Mini-plate DMAS) for future ultrafine particle (UFP) sensor network, *Aerosol Science and Technology*, **50**, 297–307.

Santos, J. P. et al. (2009), Performance evaluation of a high-resolution parallel-plate differential mobility analyzer, *Atmospheric Chemistry and Physics*, **9**, 2419–2429.

Steer, B. et al. (2014), Portable planar DMA: Development and tests, *Aerosol Science and Technology*, **48**, 251–260.

Stolzenburg, D., Steiner, G. and Winkler, P. M. (2017), A DMA-Train for precision measurement of sub-10nm aerosol dynamics, *Atmospheric Measurement Techniques*, **10**, 1639–1651.