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Comparison of instruments for particle number size distribution measurements in air quality monitoring

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Highlights

- We compared number size distributions from ELPI, SMPS, FMPS and APS
- Results from four lab generated aerosols were compared in a wind tunnel
- Good correlation was found between instruments in their middle size ranges
- At the lower and upper particle diameters there were divergences
- Particle type (size and shape) affected the correlation between instruments

Abstract

Number size distributions of airborne particles are relevant to fields including ambient monitoring, pharmaceutical and automotive measurements. A number of commercially available instruments can be used to determine particle number size distributions including the Electrical Low Pressure Impactor (ELPI), Scanning Mobility Particle Sizer (SMPS), Fast Mobility Particle Sizer (FMPS) and the Aerodynamic Particle Sizer (APS). The comparability of the data provided by these instruments has not been fully tested for different kinds of aerosols. This study compared number size distributions of laboratory generated aerosols (TiO_2, NaCl, fumed silica and soot) in a wind tunnel. Reasonable agreement was noted between the different instruments, though there were divergences. For example the ELPI was inconsistent at the upper and lower limits of its working size limits (at low concentrations). Instruments responded variably to different particle types, which has important implications for sampling heterogeneous particle mixtures such as those found in urban air. This study highlights the need for caution when comparing data obtained from different particle instruments, and demonstrates the requirement for further comparison studies in controlled settings using an assortment of particle types with the aim to standardise and harmonise particle sampling protocols.

Key words

ELPI, SMPS, FMPS, APS, number size distribution (NSD)

1. Introduction

Different particulate matter size distribution instruments are often used interchangeably, or to extend the measured particle size range within a single study, thus implying that the values they provide are comparable. Examples include studies where a combination of an ELPI (Electrical Low Pressure Impactor) and multiple SMPS (Scanning Mobility Particle Sizers) were used to analyse the vertical particle profiles on either side of a motorway (Imhof et al., 2005), and an investigation in which an APS (Aerodynamic Particle Sizer) was used to extend the SMPS sampling size range in an urban atmospheric study (Harrison et al., 2000). Some studies have illustrated that this is accurate, at least to an acceptable extent, for example in roadside particle measurements in Birmingham, UK (Shi et al., 1999a), and a study of particulate matter (PM) from motor exhausts (Ushakov et al., 2013), both of which compared results from an SMPS and an ELPI. In contrast, other studies have not identified such consistent comparability. These include a study where test aerosols were used to analyse the variability in number and mass values provided by aerosol collection equipment including an ELPI and two APS models (Pagels et al., 2005). In that study the sub-micrometre scale values measured were found to be precise and accurate, however for larger particles the ELPI and one APS model (3320) were found to overestimate the particle concentration, while the second APS model (3321) underestimated the concentration. In a study using an ELPI, APS and SMPS, while comparability was identified between the ELPI and SMPS in the sub-micrometre particle size range, the ELPI was found to overestimate the number concentrations of larger particles (Nussbaumer et al., 2008).

There is therefore uncertainty regarding the accuracy and vigour of comparing results from various instruments, especially those based on different measurement principles. It is, however, essential that these results are comparable, as the associated advantages and disadvantages of using the different particle counting techniques encourage the use of different types of equipment in different studies (Table 1). The need for standardisation of particle size distribution devices in order to provide confidence in the comparison of particle data from different instruments was stated in 2001 (Dahmann et al., 2001). Ten years later, results from further investigations (Asbach et al., 2009, Kumar et al., 2010) reaffirmed that this requirement still exists. Thus, further comparisons are needed before standardising procedures can be implemented.

While a number of studies have investigated particle size distributions in a variety of settings (e.g. atmospheric [Wehner et al., 2002], engine cycle [Shi et al., 1999b], indoor air [Long et al., 2000] and occupational exposures [Stroszejn-Mrowca and SzadKowska-Stańczyk, 2003]), studies focussing on the comparison between devices which help to validate the results from these studies and support their conclusions are more scarce. Some equipment comparison studies have dealt with near-spherical particles including Dioctyl Sebacate (DOS; e.g. Keskinen et al., 1992; Marjamäki et al., 2000) however the properties of these particles (i.e. spherical morphology and liquid state) encourage improved detection by the instruments (Van Gulijk et al, 2004). Conversely, in situations where particle number size distributions (NSDs) are of interest, for example in atmospheric studies, perfect spherical particles are less common (Shi et al., 2001). Other studies have compared results from different instruments with experimental methodologies which include sampling in urban locations (Held et al., 2008) and workplaces (Brouwer et al., 2009). While this

provides useful comparison, these are changeable environments. By ensuring that all devices are exposed to the same concentrations in a controlled laboratory setting, the variability (including particle number concentration, morphologies and sizes) to which the instruments are exposed to is reduced. Asbach et al. (2009) used such a controlled environment but compared only instruments based on electrical mobility analysis.

In this study four instruments for measuring airborne particles were compared; an Electrical Low Pressure Impactor (ELPI, Dekati), Scanning Mobility Particle Sizer (SMPS, TSI model 3936-L86), Fast Mobility Particle Sizer (FMPS, TSI model 3091) and an Aerodynamic Particle Sizer (APS, TSI model 3321) which work on different operational principles. The ELPI operates at a flow rate of 30 L/min and separates particles onto impaction plates based on their inertia, a function of their size (Keskinen et al., 1992). Particles are classified into twelve size fractions within the range 7 nm – 10 μm dependent upon their aerodynamic diameter (Marjamäki et al., 2000) with 1 s time resolution. Electrical current carried by the charged particles (imparted by a unipolar charger on entry) in each size fraction is then converted to particle number concentration. The SMPS comprises of an Electrostatic Classifier (EC) for particle sorting, followed by a CPC for particle counting (Wang and Flagan, 1990). Sampled particles are bipolarly charged to a known charge distribution in a ^{85}Kr neutralizer before they enter the EC. Particles then navigate an electrical field where their ability to pass through (dependent upon their electrical mobility, and therefore proportional to the ratio of particle charge to diameter) separates the particles. The CPC counts the mobility-classified particles and along with the known charge distribution thus allows for the calculation of the NSD. The SMPS was

operated with a long Differential Mobility Analyser (DMA) with an aerosol to sheath flow ratio of 0.3/3 l/min, thus measuring in a particle size range from 14 to 750 nm (electrical mobility diameter) with a potential resolution of 64 channels per size decade. Time resolution of the SMPS was set to 240 s scan, 20 s retrace and 40 s wait time, i.e. 5 minutes per scan. The FMPS uses the same separation principles as the SMPS, however uses a unipolar charger and utilises an array of sensitive electrometers for the simultaneous detection of the full mobility range (Crooks, 2011). The FMPS measures in the size range from 5.6 to 560 nm (electrical mobility diameter) with a resolution of 16 channels per decade and a time resolution of 1 s.

The APS works on the principle that once preliminarily accelerated, particles move at speeds in proportion to their diameter (Shi et al., 2001). Particle profiles are identified by measuring particle velocity between two laser beams, which is then converted to particle diameter. The APS measures particle size distributions in the size range from 0.5 to 20 µm (aerodynamic particle diameter) in 32 channels per size decade and with up to 1 s time resolution. In summary, the APS and ELPI determine the particle size distribution based on the aerodynamic diameter while the SMPS and FMPS are based on the electrical mobility diameter.

The aim of this study was to compare the outputs of the four aerosol sizing instruments (ELPI, SMPS, APS, FMPS) with overlapping size ranges, when challenged by four particle types with differing particle morphologies and size distributions within a controlled atmosphere.

2. Experimental

2.1 Aerosol generation

Four particle types (TiO_2, NaCl, soot and fumed silica) representing a variety of particle sizes, morphologies and chemical compositions were used to challenge the instruments. The importance of using a variety of particle types, particularly those found in urban air, or simulating particles found in urban air has been highlighted in previous studies (e.g. Khlystov et al., 2001). Soot particles were generated using an experimental soot generator (PALAS, Defined Soot Particle Generator, DSP 3000) using Ethene (C_2H_4). TiO_2 (P25, Degussa), fumed silica (Cabot, UK) and NaCl aerosols were generated using a TriJet atomizer (TriJet 3460, TSI inc.) by first dispersing a specific amount of powder in 500 ml deionised water within an ultrasonic bath for 20 minutes (TiO_2: 7.4 g/l; fumed silica: 3.8 g/l; NaCl: 10.0 g/l). After generation, TiO_2, NaCl and fumed silica were dried using two PermaPure driers (50 Nafion membranes each). The aerosol was dried with these consecutive dryers to a relative humidity of <20%. Soot particles were introduced directly before the flow straightener (Figure 1), while TiO_2, NaCl and fumed silica were introduced into the mixing chamber. Particles were not neutralized prior to injection into the wind tunnel.

2.2 Measurement set-up

Measurements were conducted in a wind tunnel at the Institute of Energy and Environmental Technology (IUTA), Duisburg, Germany. Flow rate was set to 1000 m^3/hr which corresponded to a speed of 1.3 m/s within the tunnel at the sampling points. The instruments were connected to the wind tunnel through four inlets with different diameters, each pre-calculated to allow isokinetic sampling (Table 2). At the point of sampling, the wind tunnel had a width and height of 63 cm. Sampling inlets were located in the centre of the wind tunnel with a spacing of 5 cm

(Figure 1). A hygrometer (temperature and humidity probe from Hygrosens), placed after the sampling inlets 20 cm below the upper wall of the wind tunnel, was used to monitor relative humidity and temperature during the measurements. The temperature was nearly constant for all measurements with a value between 20° - 21° C for the TiO_2, NaCl and soot measurements and of 18°C for the fumed silica measurements. The relative humidity differed for the substances and the following values were observed: TiO2: 45% rH, NaCl: 41% rH, fumed silica: 36% rH. At the beginning of the soot measurements the humidity had a value of 35 % rH which changed within 0.5 hours to a value of only 17 % rH. All instruments were exposed to identical rH conditions during measurement.

Sampling inlets were located 2 m down-tunnel of a flow straightener, and therefore laminar and uniform flow at the instrument inlets was assumed during sampling. After the point of sampling a HEPA filter was used to efficiently remove particles. The number concentration of particles during measurement was approximately 10^4-10^6 particles/cm^3, which was suitable for the instruments included in the study. Particle Number Concentrations (PNCs) were left to stabilise before the measurements took place. This eliminates the effects of "influx events" which could affect the SMPS measured concentrations (Wright, 2014). These "influx events" are short term increases in PNC, such as may be found at the roadside and can affect instruments with lower time resolution. The ELPI, FMPS, SMPS and APS had individual sampling inlets. Due to different instruments requiring different flow rates, each inlet had different inner diameters which were configured for the individual instrument to provide isokinetic sampling (Table 2). The instruments were connected to the inlets using flexible inert tubing which was as short as was practically possible. The

concentration of the particles in the wind tunnel was not accurately controlled because the focus was a comparison between instrument responses rather than measuring absolute values of PNC. Diffusion and other losses were not taken into account as in previous studies (Leskinen et al., 2012).

2.3 Sampling periods

Each sampling period consisted of two hours of particle measurement at fairly stable PNC (PNC varied by around 10% during the measurement period for TiO_2, silica and soot, and by around 30% for NaCl in comparison to the mean concentration value). The ELPI was cleaned and collection substrates replaced after each sampling period. The instruments counted particles in different size bins and used different particle sizing methodologies (electrical mobility/aerodynamic), making comparison more difficult (Khlystov et al., 2001; Table 2). In this study comparison was made between the NSDs based on the aerodynamic diameter of the particles as provided by the different instruments. The ELPI and the APS directly measure the aerodynamic diameter of airborne particles. The measurements of the SMPS and FMPS were converted from electrical mobility diameter into aerodynamic diameter using an effective density for each particle type. The effective density was chosen so that the measured size distribution of the APS and SMPS gave a near-continuous NSD over the whole measurement size range. Instrument model type, model description and inlet details are provided for each of the devices used in the comparison in Table 2. Further information on the handling and theory of operation for the different instruments is available within the manuals provided by the manufacturers.

3 Results

The NSDs of the different substances are shown in Figure 2 as a function of aerodynamic diameter. All distributions showed particles over the whole size range with modal diameters of ranging from 25 nm for soot, 80 nm for NaCl, 105 nm for TiO2 and 110 nm for fumed silica.

Between 50 and 300 nm reasonable agreement was noted between the measurement devices (particle number concentrations within 25 %; SMPS, FMPS and ELPI) for TiO_2 (Figure 2a). Below 50 nm, the ELPI showed higher concentrations of particles in contrast to the SMPS and FMPS. Above 1 µm, the ELPI measured higher concentrations than the APS. Generally, the APS was shown to extend the sampling range of the SMPS for TiO_2, with reasonable overlap. The standard deviations of the results provided by a single instrument were generally small, indicating stable number size distributions during the measuring period; however at the outer size limits of the detection ranges of the ELPI and APS the variation was greater. In contrast, standard deviations for the FMPS and SMPS were consistent throughout their sampling ranges. While the SMPS, ELPI and APS correlated to a unimodal distribution, the FMPS data showed a bimodal distribution.

For NaCl (Figure 2b), the SMPS, FMPS and APS showed satisfactory agreement between distributions. Standard deviations were low, except for particles below 20 nm measured with the FMPS, and some size fractions measured with the APS. In contrast to the unimodal distribution shown by the SMPS, FMPS and APS, the ELPI displayed a bimodal distribution, with a peak below 20 nm which was significantly greater than measured by the SMPS and FMPS. A concentration minimum was noted at around

85 nm in contrast to the correlating SMPS and FMPS data. As for TiO_2, above 1 µm the ELPI measured values higher than the APS; however the shape of the distribution was comparable.

For soot particles (Figure 2c) there was agreement of a bimodal distribution with peaks at 25 nm and 110 nm by the SMPS, FMPS and ELPI, though some deviation was noted with regards to the FMPS following the second peak where values obtained were lower than provided by the other instruments. There was discontinuity in the overlapping portions of the SMPS and APS, with much lower concentrations observed by the APS in comparison to the SMPS, FMPS and ELPI, and with a differing distribution shape. Standard deviations for the SMPS and FMPS were small, and this was also generally the case for the ELPI and APS.

While the instruments provided relatively comparable data for TiO_2, NaCl and soot, in the case of fumed silica (Figure 2d), much more variability was noted between the different particle size distributions. Agreement of data from the SMPS, FMPS and ELPI was noted between 150 nm and 500 nm (within 15%), and this extended to between 60 nm and 600 nm (within 8%) when considering only the SMPS and FMPS. The ELPI showed higher concentrations of particles than the other instruments in those size ranges below 100 nm and above 1 µm. Similarly to TiO_2, the particle number size distribution for fumed silica provided by the FMPS was bimodal, in contrast to the other samplers, which all provided a unimodal distribution. Again, the ELPI and APS showed greater standard deviations in the upper sections of their working ranges, with the FMPS also showing increased variability in the lower section of its measuring range.

4. Discussion

4.1 Calculation of effective density

In order to make the NSDs measured by the different instruments comparable, the data from the FMPS and SMPS were converted to aerodynamic diameter using an assumed value of effective density for each of the substances (Equation 1), where D_{ae} = aerodynamic diameter, D_m = mobility diameter, ρ_p = effective particle density, and ρ_0 = density of water.

$$D_{ae} = D_m\sqrt{(\rho_p/\ \rho_0)} \qquad \text{Equation 1}$$

The effective density was chosen to obtain a smooth NSD over the whole size range according to the SMPS/ APS data within the overlap region, and to compare to literature density values. This method has been used in previous studies (e.g. Pitz et al., 2011). The effective density used for NaCl particles was 2.164 g/cm^3, nearly identical to the bulk value of 2.165 g/cm^3 (Lide, 2004). This very good agreement is due to the fact that NaCl forms compact particles. The bulk density of TiO_2 particles is approximately 4.000 g/cm^3 (Dewalle et al., 2010), however in this study, to reflect the agglomerated nature of the particles and to provide fit between APS and SMPS, an effective density of 0.900 g/cm^3 was used. This low effective density indicates that the TiO_2 were loosely packed agglomerates. The effective density used for soot particles was 1.700 g/cm^3. This was within the density range of soot agglomerates identified in previous studies of between 0.560 and 1.780 g/cm^3 (Zhang et al., 2008, Evans et al., 2003). In a previous study, for fumed silica particles of 10 nm size, an effective density similar to the bulk density was identified of 2.200 g/cm^3 (Keskinen et al.,

2011). For larger, loose agglomerates the effective density would be lower, as in this study, and a density of 1.300 g/cm^3 provided continuity to SMPS/ APS data.

4.2 Comparison of instrument performance

SMPS and FMPS

For all four measured particle types, the SMPS was generally found to correlate well with the FMPS (Figure 2). This was especially the case for NaCl and soot particles, which was interesting since these particles possess very different morphologies (Asbach et al., 2009), and in this study had differing modal particle diameters (obtained from NSDs) of approximately 80 nm and 25 nm respectively. A previous comparison of a SMPS and a FMPS in a laboratory study testing salt and gold particles produced highly comparable results (Jeong and Evans, 2009), though multimodal NSDs were identified from the FMPS. This effect was also seen in two of the sampled particle types in this study; TiO_2 (Figure 2a) and fumed silica (Figure 2d). A peak not identified in the SMPS data was noted at 15.7 nm aerodynamic diameter, corresponding to 16.5 nm electrical mobility diameter in the TiO_2 and fumed silica FMPS data. This is comparable to previous studies which have identified a small peak at 10 nm (using salt particles; Asbach et al., 2009) and 10.7 nm (using salt and gold particles; Jeong and Evans, 2009). It has been proposed that the erroneous FMPS peaks were a result of the algorithm used in the conversion of raw data to a size distribution in the FMPS (Jeong and Evans, 2009). This was only observed for SiO_2 and TiO_2 particles, and not for soot and NaCl. This may be due to the low concentration of particles for the former two materials in comparison to the latter two materials which had concentrations two and three orders of magnitude higher. The FMPS is considered a less sensitive instrument than the SMPS (Morawska et al.,

2009), and there has been little research focused on the accuracy of data provided by the FMPS and how it relates to other sampling instruments. In this study the FMPS was generally found to correlate well with SMPS data, however there are clearly divergences, specifically below 50 nm aerodynamic diameter, and it is currently unknown whether this is a particle size or particle morphology effect (Asbach et al., 2009), or the result of another aspect of the sampling procedure entirely.

ELPI

Particle NSDs measured by the ELPI generally showed agreement with the SMPS, FMPS and APS, however this agreement was much poorer at the upper and lower ends of the ELPI working range, especially for TiO_2, NaCl and fumed silica. This general comparability acknowledged between the ELPI and the other instruments has been identified in a number of studies investigating different particle types, including monodisperse and polydisperse DOS (Hillamo et al., 2000), biomass combustion (Nussbaumer et al., 2008), atmospheric urban studies (Shi et al., 1999a), and engine test bed systems (Shi et al., 1999b). In the engine test bed system and atmospheric study a filter stage was not used, meaning particles below 30 nm were not measured. In this study, data from the filter stage (7-28 nm) was found to be significantly higher than the other instruments for TiO_2, NaCl and fumed silica. The apparent overestimation of particle counts in the nano-size range has been noted in previous studies (Maricq et al., 1999; Held et al., 2008). This disparity has been attributed to the differing sizing principles between the ELPI (aerodynamic diameter) and the SMPS (electrical mobility diameter). Additionally, particle bounce (Marjamäki et al., 2000) and particle deagglomeration (Brouwer et al., 2009) might play a role. In this study, ELPI overestimation on the filter stage was found for not only agglomerates

but also compact particles, for example NaCl. This suggests that particle deagglomeration was unlikely to be a predominant cause of overestimation. Particle bounce has previously been identified to cause increases in PNC at the lower working range of the ELPI (e.g. Leskinen et al., 2012). Due to the high impaction velocity, particles which bounce have been found to collect on the filter stage of the ELPI (Virtanen et al., 2010), thus increasing the current produced by this size bin.

The ELPI measured significantly higher levels of coarse particles than the APS for TiO_2 and fumed silica, a finding which replicated previous studies (Hillamo et al., 2000; Evans et al., 2003). This has been hypothesised by these authors to be a result of the low number of particles in the coarse size fractions or the low total charge that these particles carry which would be consistent with the small mean diameters of particles generated in this study.

The length of sampling may have been an additional factor affecting the reliability of the particle data at the upper and lower size limits of the ELPI. Previous laboratory studies have shown that after sampling periods of 60 seconds (Van Gulijk et al., 2001) and 20 minutes (Maricq and Xu, 2004) there can be a shift in the particle size distribution. Particles build up on the substrate surface during the collection period into “domes”. These have the potential to affect the cut off diameters for the different stages and cause particle bounce, shifting the modal diameter towards more coarse particles. In addition, the ELPI has a more coarse size resolution that the other instruments, which means that part of the detail in the size distributions is missing. This might account for a portion of the difference between size distributions.

APS

The APS was found to extend the sampling range of the SMPS for NaCl and TiO_2 in this study, though standard deviations of observed values became large above 4 µm in the case of TiO_2. This continuance of SMPS data was similar to a previous traffic study (Harrison et al., 2000). However, the APS has been previously found not to handle fluffy agglomerates well (Tsai et al., 2008). This was identified in this study in the largest size fractions. The APS accelerates particles with a defined force in a nozzle. 'Fluffy' or loose agglomerates may tend to deagglomerate in this nozzle and this may lead to discontinuities when comparing values with other particle sizers. In addition particle losses from the APS, potentially at the surface of the inner nozzle due to inertial impaction, have previously been found (Tsai et al., 2008) which may also affect the signal.

4.3 Response to different particle types

For the assessment of instrument comparability, four particle types (TiO_2, NaCl, soot and fumed silica), which exhibit different sizes and morphologies were chosen. The differing particle sizes, morphologies and particle compositions were intended to simulate the variety of particle types encountered in the studies in which these samplers are often used, including outdoor air, indoor air, exhaust studies and occupational exposure (Asbach et al., 2009). Though there were some consistent trends between particle types, for example the ELPI generally measuring higher particle numbers than the other instruments at its upper and lower working size limits, the instruments often behaved differently in reaction to different particle types. For example, the FMPS successfully identified a unimodal NSD for NaCl, however in contrast to the other instruments provided a bimodal distribution for TiO_2 and fumed

silica. This has important implications for heterogeneous aerosol sampling; as there is potential for particles from complex mixtures, for example urban air, to be skewed according to preferential counting and/ or collection. While the instruments have been previously known to produce artifacts within the data, for example the FMPS (e.g. Asbach et al., 2009) and ELPI (e.g. Evans et al., 2003), additionally their reaction to differing particle types has significant sampling effects. Importantly, the properties of the particles (for example size, morphology or composition), responsible for the changing efficiencies of the instruments cannot be elucidated from studying only four particle types. There is therefore a requirement for further investigations with these instruments with a larger number of different particle types.

4.4 Effect of differing collection principles

The SMPS and FMPS size particles according to their electrical mobility diameter; particles are separated in an electrical field. In contrast, the ELPI and APS size particles based upon their aerodynamic diameter, with the ELPI separating particles based upon inertial impaction and the APS separation related to single particle time of flight between two laser beams. The aerodynamic diameter is the diameter of an equivalent spherical particle with a density of 1 g/cm^3 that standardises for morphology and density (Rostedt et al., 2009). The electrical mobility diameter standardises differently for morphology and not for density; particles are classified based upon their efficiency at crossing an electric field. These differing sizing principles may have significant implications for derived NSDs, for example with soot agglomerates (Van Gulijk et al., 2004). The differing sizing metrics employed by the instruments has previously been cited as a potential source of error when comparing

data collected simultaneously by these instruments (e.g. Shi et al., 1999a; Evans et al., 2003).

5. Conclusion

This study has compared the results from four instruments sampling from the same airstream for four particle types. This comparison has shown that different instruments provide generally similar results in a controlled sampling setting. Divergences were generally noted at the lower and upper working size ranges of the instruments and at low number concentration. Where differences were noted, these could be a response to the different operating procedures used by the instruments and/or the different particle types that were sampled. Further work should focus on the complete characterisation of homogeneous aerosols in order that a clear analysis of the effects of particle characteristics (e.g. morphology and size) on the different instruments can be assessed. There is a requirement for standard protocols in aerosol measurement and primary standards for particle number and size.

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Figures

Figure 1: Schematic of experimental setup. After generation of the aerosol using the trijet and introduction into the mixing chamber, the aerosol has to pass the flow straightener. The distance of the flow straightener to the inlets of the different measurement devices is above 2 m to provide a laminar flow profile. Isokinetic sampling was ensured by different inlet diameters selected according to the wind speed within the tunnel and flow rate of the different devices.

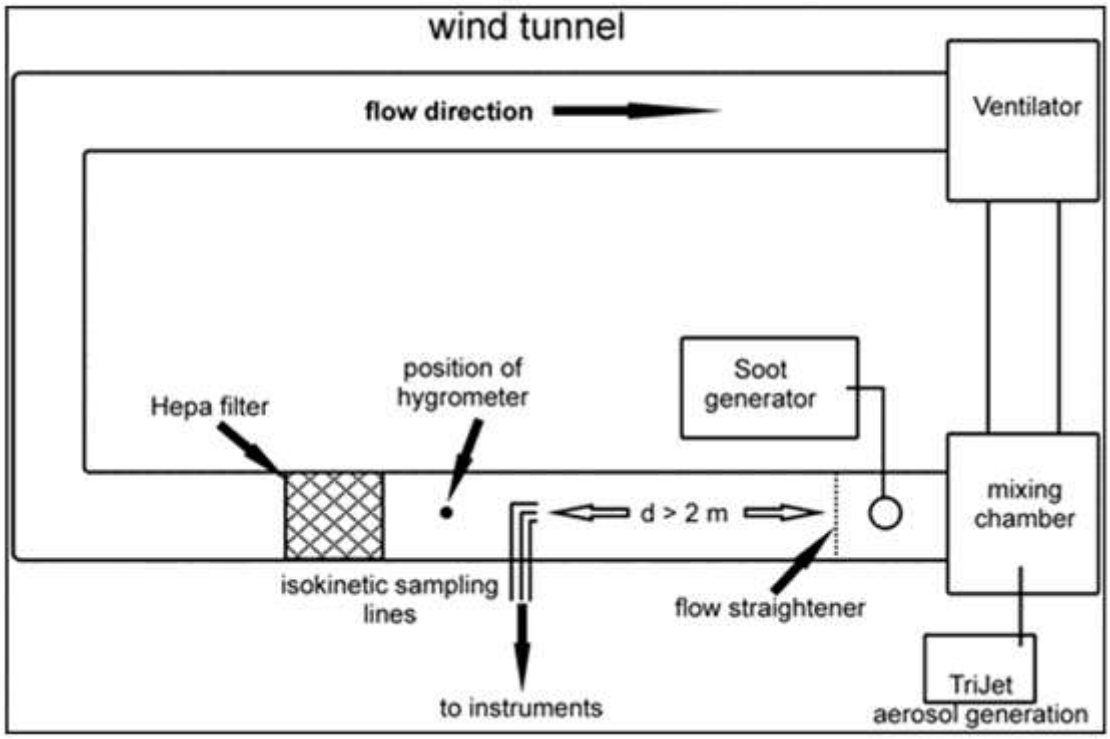
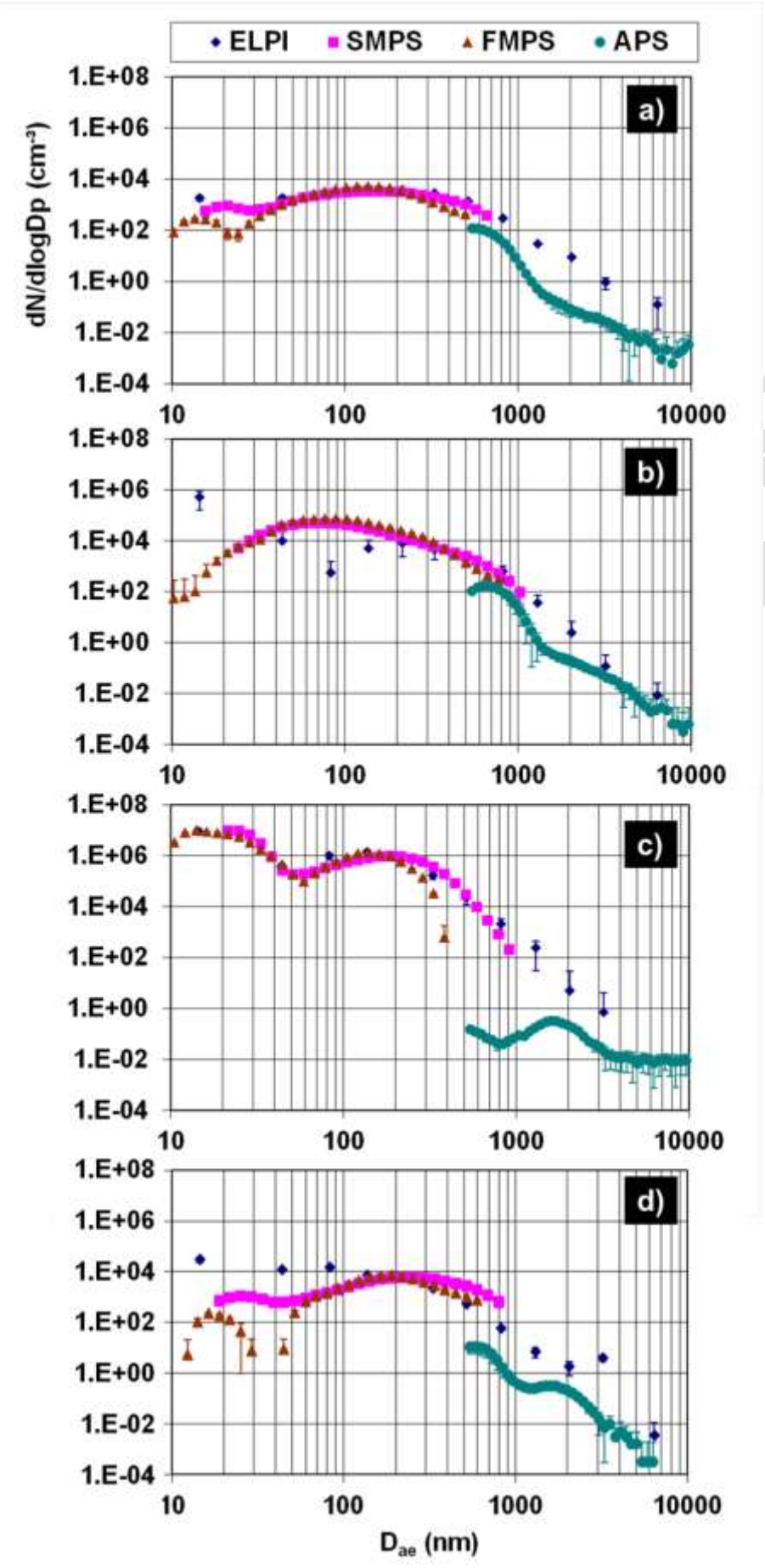


Figure 2: Comparison of the number size distributions (by aerodynamic diameter) provided by the four instruments (ELPI, SMPS, FMPS and APS) for the four tested substances. Error bars are shown for each data point (though these are sometimes smaller than the data point itself) and = 1 standard deviation ± mean of sampling period. a) TiO_2 particles. An effective density of 0.900 g/cm^3 was assumed for the particles. b) NaCl particles. An effective density of 2.164 g/cm^3 was assumed for the particles. c) Soot particles. An effective density of 1.700 g/cm^3 was assumed for the particles. d) Fumed silica particles. An effective density of 1.300 g/cm^3 was assumed for the particles.


ELPI
SMPS
FMPS
APS
a)
b)
c)
d)
dN/dlogDp (cm⁻³)
1.E+08
1.E+06
1.E+04
1.E+02
1.E+00
1.E-02
1.E-04
10
100
1000
10000
Dae (nm)

1

Tables

Table 1: Advantages and disadvantages of the sampling instruments used in this study.

Instrument (model used in this study)	Operating particle size range	Example type of study used in	Advantages	Disadvantages
ELPI	7 nm–10 μm	Atmospheric, occupational	Large size range, excellent time resolution	Classic drawbacks of cascade impactors e.g. particle bounce. Low size resolution
SMPS	14–730 nm	Atmospheric, occupational	High size resolution, ability to sample very small particles; applications in atmospheric studies	Slow time resolution
FMPS	5–550 nm	Occupational, fuel cycle, wood burning, emissions	High size resolution, fast scan time, ability to sample very small particles; applications in atmospheric studies	Less sensitive than SMPS
APS	0.5–20 μm	Atmospheric, occupational	Extends particle size range when used in combination with SMPS, high size resolution	Limited size range; unsuitable for atmospheric studies with the importance of nano-sized particles

1 **Table 2: Overview of the different instruments used for particle measurement.**

Instrument	Type/model	Inlet diameter (mm)	Flow rate (l/min)
FMPS	TSI, model 3091	15.5	9.8
SMPS	TSI, model 3080 with long DMA, model 3081	9.3	0.3
APS	TSI, model 3321	10.7	4.2
ELPI	DEKATI, outdoor air ELPI with filter stage	28.1	29.4

2