NanoScan SMPS - A Novel, Portable Nanoparticle Sizing and Counting Instrument

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Abstract. A novel instrument, the NanoScan SMPS (TSI 3910), is introduced here that provides the capability of employing well-established Scanning Mobility Particle Sizing (SMPS) technology in a format that can be easily utilized in the field. The use of a non-radioactive unipolar charger, radial Differential Mobility Analyzer (rDMA) and isopropanol-based Condensation Particle Counter (CPC) removes transport and application restrictions on occasion encountered with current SMPS technology. The NanoScan SMPS was compared initially to a TSI component SMPS reference system using several sizes of monodisperse silver particles. A further comparison was completed with polydisperse NaCl and Emery Oil particles. A linearity test for the instrument was performed by comparison to the ultra-fine butanol CPC (TSI 3776) as concentration reference. Subsequently, in-vehicle measurements during a freeway journey between two German cities were made to provide an example of everyday exposure to nanoparticles while driving. Coupling continuous in-vehicle measurements with GPS technology enabled an easy on-route characterization of particle size distributions, allowing source appointment of measurements, identification of evident hotspots as well as a variety of other sources of interest. Finally, the NanoScan SMPS was applied to different processes within a production test facility. Here direct comparisons between ventilation (background) and in the breathing zone were made. These measurements demonstrated the variation between the nature of the nanoparticles in the ventilation system from those within the breathing zone. During all tests the NanoScan SMPS was found to provide data that compares very well with that of the reference SMPS. It also showed a clear linearity with the CPC measurement up to concentrations as high as 10⁶ particles/cm³. In conclusion, the NanoScan SMPS was found to be a reliable tool for nanoparticle sizing and counting in applications where current SMPS instruments would prove to be challenging.

Keywords: SMPS, CPC, particle measurement, in-vehicle, exposure monitoring, ventilation, breathing Zone
1. Introduction

There are numerous sources of nanoparticles, including a large variety of anthropogenic origin such as engineered nanoparticles and particles from combustion and industrial processes. However, nanoparticles are also ubiquitous in ambient air, both indoors and outdoors. The size distribution, number concentration, and surface area of such nanoparticles represent key parameters in the determination of their risk, as has been identified by many recent health studies. Oberdörster et al., 2005 reported a high rate of pulmonary deposition of nanoparticles, and their ability to travel from lung to systemic sites as well as their high inflammation potential. Particles in the nanometer range are more biologically active due to their greater surface area per mass (Gurr et al., 2005). However, only few specific types of particles are studied in depth (e.g. asbestos) that allow an estimation of their potential health impacts (Sanchez et al., 2009). Measuring exposure to nanoparticles has typically been conducted as academic research using high-end instrumentation and sophisticated software. For many applications, e.g. in the field of indoor air quality and occupational health and safety, this may not be necessary. Hence, the ability to characterize the properties of airborne nanoparticles to a similar level of accuracy and resolution similar to that of the current state-of-the-art laboratory-based research instruments is at the fore-front of the current air quality measurement needs.

This paper introduces a novel instrument and provides the validation of it through direct comparison to the standard SMPS technique. It will also offer insight into the application of the NanoScan SMPS to the measurement of aerosols within environments that would be challenging to apply the component SMPS that is frequently used in the laboratory environment.

The application of the Scanning Mobility Particle Sizing (SMPS) technology to the air quality monitoring field by researchers has provided a level of detail that has become standard within the community in terms of sizing accuracy and detail of the information delivered. Hence, taking this technology from the laboratory into the field is a desirable next step. With regards to portable sizing, the current state-of-the-art is the application of advanced optical measurement technology like the one of the Optical Particle Sizer (OPS, TSI 3330). Despite providing detailed size distribution information, the absence of particle growth technology within the instruments limits it sizing capability to particles larger than 300 nm. Hence, it does not provide the resolution and small sizing capability that has become customary with laboratory-based research equipment such as the component SMPS. The NanoScan SMPS (TSI 3910) was designed to provide size resolution and accuracy in the field close to the one researchers have grown accustomed to within the laboratory. It utilizes the proven technology of electrical mobility sizing and particle detection. In the instrument nanoparticles are charged, classified by their size and subsequently counted in a particle counter. The latter magnifies these small particles by condensing liquid onto their surface to a size that is detectable in a laser optic assembly. The number distribution is based on a mobility equivalent diameter.

The NanoScan SMPS has been designed for multiple applications such as monitoring of industrial process emissions and workplaces, mobile studies, in-vehicle and outdoor air quality measurements. Number size distributions of nano-size airborne particles in the range from 10 to 420 nm can be obtained. The size range can be extended to coarse particles with an additional compact, portable instrument, the Optical Particle Sizer (OPS). Together these instruments can cover the full range from 10 nm to 10 µm. The instrument includes a built-in computer, is battery-powered and contains no hazardous substances (neither butanol, nor radioactivity) that could restrict its use to designated areas.

There are two key features of the instrument that enable its portable use: The first is a patented opposed flow unipolar diffusion charger (Medved et al., 2000), which works without any radioactivity and thus avoids related transport issues. The second is the incorporation of a radial Differential Mobility Analyzer (rDMA) in the instrument. The radial DMA technology was introduced by Pourpix and Daval (1990), followed by work done by Zhang et al., 1995 and Fissan et al., 1998. As
opposed to the cylindrical DMA developed by Knutson and Whitby (1975), the sheath and sample air flow radially inwards between two flat electrodes in this DMA type.

2. Instrumentation: Working Principle and Features
Prior to discussing the internal workings of the NanoScan SMPS, the exterior of the instrument is introduced here in Figure 1A, along with a visualisation of the data output given on the on-board computer’s color-touch screen (Figure 1B).

Figure 1: A) The NanoScan SMPS (left) and B) the instrument’s color touch screen, showing the output of a measurement in SMPS mode (right).

The internal operation of the NanoScan SMPS is outlined in Figure 2. The four main components of the instrument are its inlet cyclone, the opposed flow unipolar diffusion charger, the radial DMA and the isopropanol CPC.

Figure 2: NanoScan SMPS flow schematic with the main internal components inlet cyclone, patented unipolar charger, rDMA and CPC highlighted.
On entering the instrument, the aerosol flow (0.75 L/min) is pre-conditioned to remove large particles by the cyclone which has a cut point ($D_{50}$) of 550 nm. The cyclone is crucial for long-term use of the instrument as it prevents the issue of plugging that can occur within an impactor. After that the polydisperse aerosol enters the patented unipolar charger, which is a corona jet type charger (Medved et al., 2000). This unipolar charger works through the introduction of an opposed charger flow that is filtered with both an active carbon filter and a HEPA filter. After passing over the charger needle, a jet of positive ions flows into the field-free mixing chamber, allowing the interaction of ions with the polydisperse sample flow using the opposed flow technique, which improves mixing and charge repeatability. After flow splitting, 0.25 L/min of the sample flow enters the radial DMA. The remaining flow enters as particle-free sheath air from the bottom outside edge of the rDMA into a circular channel. The polydisperse sample flow is introduced tangentially through an inlet channel at the top. The top plate of the rDMA is at ground, and the bottom plate is at a high negative voltage, thus creating an electric field. More details on the radial DMA technique can be found in Zhang et al., 1995 and Fissan et al., 1998. The size classified aerosol exits out of the bottom center port of the rDMA through the ‘monodisperse outlet’ and continues to the isopropanol-based Condensation Particle Counter (CPC). This CPC is based on the handheld CPC design (TSI 3007) that was introduced several years ago and is well-described in Hämmeri et al. (2002). The excess flow exits through the top center port of the rDMA.

During the course of a measurement the DMA’s voltage is ramped up to scan the entire size range. During every 60 second sampling time there is a 45 second up-scan in which the measurement occurs, and a 15 second down-scan (retrace). This describes the size distribution measurement mode of the NanoScan SMPS (SMPS, see Figure 1B). In the second mode, the so-called Single mode, the instrument monitors the aerosol concentration at a single electrical mobility diameter with a resolution of 1 second. The mobility diameter can be set by the operator to particle sizes between 10 and 420 nm. This single mode enables for instance detection and tracing of a specific engineered nanomaterial of a known size.

The NanoScan SMPS can run on battery power for several hours and its on-board data storage is sufficient for 8 to 10 days of continuous operation. The USB storage drive option can be used to export the data. Data acquisition can be done conveniently via a computer with dedicated measurement software. This is especially useful when the instruments runs in its extended mode on A/C power and with an external working fluid reservoir connected. Further details can be found on the TSI webpage/specification sheet.

3 Results and Discussion

3.1. NanoScan SMPS Verification and Validation Tests

A direct comparison was made between the NanoScan SMPS and two research-grade SMPS systems commonly used in the laboratory (TSI 3034 and TSI 3936L76). The proven technology of the SMPS was used as the reference in several applications. The tests involved challenging the NanoScan SMPS with both monodisperse and polydisperse aerosols. The monodisperse aerosol consisted of silver (Ag) particles generated by a furnace according to Scheibel and Porstendörfer (1983). The corresponding data are shown as upper graphs in Figure 3. The polydisperse aerosols were made from NaCl and Emery Oil (EO, poly-alpha-olefin, PAO 4 cSt). EO generated by an Electrospray Aerosol Generator (TSI 3480) provides spherical particles of synthetic lube oil. Buffer and EO solutions were prepared according to TSI Application note EM-004, 2006, TSI Inc., Shoreview, MN, USA.
Results of the comparison of the NanoScan SMPS with the reference SMPS involving both monodisperse (Ag) and polydisperse (NaCl & EO) aerosols are shown in Figure 3. The data agree very well for the smaller sizes (13.3 and 23.7 nm), although the coarser resolution of the NanoScan SMPS is noticeable. For the monodisperse 133 nm silver particles, the mode agrees as well but a broadening is visible in the results of the NanoScan SMPS. For the polydisperse comparison and validation, NaCl and EO were chosen. Despite the lesser 13 channel resolution of the NanoScan SMPS, the measurements reveal an excellent correlation to the 64 channel/decade resolution of the component SMPS utilized for the two data sets (see lower panels in Figure 3).

Figure 3: Upper graphs: Parallel NanoScan SMPS and SMPS (TSI 3034) scans of classified Ag aerosol at 13.3, 23.7 and 133 nm. Lower graphs: Scans of polydisperse NaCl and Emery Oil.

The concentration linearity of the NanoScan SMPS was then verified by comparison to an ultrafine butanol CPC (TSI 3776). The results highlighted during the presentation (not shown here) demonstrated a clear concentration linearity of the NanoScan SMPS up to $10^6$ particles/cm$^3$. In addition the NanoScan SMPS was also successfully compared to a Fast Mobility Particle Sizer (FMPS, TSI 3091) during measurements of a workplace aerosol originating from soldering.

3.2. In-Vehicle Measurements –Mobile Study

Due to the ever increasing amount of time spent within vehicles, they represent an important location with regards to workplace exposure. Hence, a mobile study of in-vehicle measurements was conducted
through the continuous measurement of in-vehicle air during a journey from Cologne to Bremen in Germany (380 km distance). The NanoScan SMPS was placed on the front seat of the car with its sampling port open to sample the cabin air of the vehicle. The measurements were completed by a GPS tracker to enable the accurate correlation of data reported by the instrument with the sampling environment. Figure 4 summarizes the data set, showing the total number concentration plotted on a Google Earth map.

Figure 4: The total particle number concentration during the mobile study shown in Google maps. Warmer colors indicate higher particle concentrations.

Results for the total number concentration and the geometric mean diameter of the measurements calculated from individual recorded number size distributions are displayed in Figure 5A and 5B. Note that figure 5A shows the same total concentration data as Figure 4.

As can be seen from Figure 5A, the variation in the total number concentration measured along the route highlights a number of distinct high particle number hot spots such as in Munster (see Figure 5, iii) where a concentration of 227,444 particle/cm$^3$ was recorded. It is clear from the size distribution measured that the majority of the particles within this situation are very small, with diameters smaller than 20 nm. The largest particles were found at a construction site at the Lohne-Dinklage location. Here the mode of the distribution is at 86.6 nm (see Figure 5B). The results taken at Bremervörde are the final example of the different nature of particle size distributions along the route. Here the mode of the distribution is at 36.5 nm and particle concentration is low.

With regards to the geometric mean diameter variation over the course of the drive it is clear that there appears to be some degree of correlation between the total number concentration and particle size along the route. This is indicated by the areas shown as hotspots in terms of total number concentration, which display particle size distributions with a geometric mode that is less than 20 nm. In contrast the sites with lower total number concentration exhibit a geometric mean that is approximately 40 to 50 nm in diameter. This implies that sites with higher total number concentration are influenced to a greater degree by aerosols generated by combustion processes as indicated by Figure 5i, whereas those areas demonstrating a lower total number concentration are influenced to a greater degree by aerosols generated by mechanical processes such as construction, as indicated by Figure 5iii. This study demonstrates the value of such data but also shows that nanoparticle concentrations at common “work” places such as inside a vehicle can be very high.
Figure 5: The total particle concentration (A) and geometric mean diameter in nm (B) of the aerosol in the car driving from Cologne to Bremen in Germany. The graphs to the right show the size distributions with 13 channels of resolution at: Bremervörde (i); a construction site in Lohne-Dinklage (ii); and Munster (iii). Their approximate location is indicated on the maps of panels A and B.

3.3. Indoor Air Monitoring

Nanoparticles at indoor workplaces represent an important area of environmental monitoring. Hence, the NanoScan SMPS was also tested in a production facility. Utilizing the NanoScan SMPS, an assessment of worker exposure was made during several work scenarios. These ranged from material tests like abrasion and extrudability to measurements done during milling of the same material. The background particle concentrations in indoor air and exposure levels during the material processing were determined. Background particles were measured at each site and at several sampling points within the rooms. Exposure to nanoparticles was measured in the breathing zone. The background data recorded from the ventilation diffusers supplying fresh air to the rooms were measured, along with the breathing zone during all processes.

The particle size distributions measured at a number of different risk areas inside an indoor production facility are summarized in Figure 6. Different processes result in the generation of nanoparticles which pose a known risk within a work place. Hence, concrete measures could be taken within the facility to limit their impact on the employees. One such measure is the use of enclosures and glove cabinets. Figure 6B shows data from the NanoScan SMPS while the efficiency of the enclosure is challenged.
With regards to the data shown in Figure 6A, background particles were measured from the ventilation diffusers that supply fresh air to the laboratories and at several sampling points within these rooms. By averaging the data from all locations studied, it was found that the total number concentration in the fresh air supplied through diffusers from the ventilation system was around 6,100 particles/cm\(^3\) in the nanoparticle size range (< 0.5 µm). In contrast the total number concentration of particles in the breathing zone during the various processes was found to be twice that, with concentrations on the order of 12,000 particles/cm\(^3\). The dominant peaks in the size distribution within the breathing zone were determined to be approximately 15 and 37 nm. In the background signal a third peak was evident at about 116 nm, which is a particle size not uncommon for indoor aerosols.

**Figure 6:** NanoScan SMPS data from measurements of nanoparticles in indoor air during material production at a test facility. (A) The blue line represents data from the ventilation diffuser system and corresponds to background. The red line represents data taken in the breathing zone during the material processing. (B) NanoScan SMPS scans from the emissions generated during a composite mixing process, aimed at testing the efficiency of the enclosure.
The efficiency of enclosures employed as a safety measure is highlighted from the analysis of the measurements during a composite mixing process, which took place in a ventilated enclosure (Figure 6B). It is clear that the particle counts in the room air measured at the ventilation diffuser were equal to the background measurements in the enclosure. The total number concentration was determined to be on the order of 4,700 particles/cm$^3$. As the material is processed within the enclosure, the number concentration within the enclosure increased by a factor of four to about 20,000 particles/cm$^3$. Therefore it is evident that the enclosure was able to capture the majority of the particles emitted. Despite this fact about 8,600 particles/cm$^3$ were still measured in the breathing zone, which is approximately twice that of the background.

4. Conclusions

This paper described the new NanoScan SMPS (TSI 3910) and highlighted its capabilities as a reliable instrument for real-time nanoparticle measurements within the range from 10 to 420 nm. The NanoScan SMPS provides the means to employ SMPS technology in a format that can be easily utilized in the field. The incorporation of a unipolar charger, rDMA and isopropanol-based CPC removes transport and application restrictions currently in place for SMPS technology. The NanoScan SMPS demonstrated concentration linearity up to $10^6$ particles /cm$^3$. It provided good comparability to the laboratory-based reference SMPS systems when challenged with monodisperse silver and polydisperse NaCl and EO particles. Two case studies with the NanoScan SMPS demonstrated the wide range of possible applications and ease of use of this portable instrument. Coupling continuous in-vehicle measurements with GPS technology enabled an easy characterization of the particle size distributions while driving from Cologne to Bremen in Germany. This allowed source apportionment based on measurements, highlighting distinct hotspots and sources of interest. It also allowed an assessment of the exposure to nanoparticles in the vehicle as a workplace. Finally measurements within a production test facility showed the variation between the nature of the nanoparticles in the ventilation diffusers compared to those detected in the breathing zone.

5. References

Fissan, H.; Pöcher, A.; Neumann, S.; Boulaud, D. and M. Pourprix, Analytical and empirical transfer functions of a simplified spectromètre de mobilité electrique circulaire (SMEC) for nano particles. Journal of Aerosol Science 29, 3: 289-293, 1998.

Gurr, J.R., Wang, A.S.S., Chenb, C-H. and K.Y. Jan, Ultrafine titanium dioxide particles in the absence of photoactivation can induce oxidative damage to human bronchial epithelial cells. Toxicology, 213: 66-73, 2005.

Hämeria, K., Koponen, I.K., Aalto, P.P., and M. Kulmala, The particle detection efficiency of the TSI-3007 condensation particle counter. Journal of Aerosol Science 33, 1463–1469, 2002.

Kaufman, S.L. and F.D. Dorman, Aerosol Charge Adjusting Apparatus Employing a Corona Discharge. US Patent 6,544,484 April 8, 2003.

Kinney, P., Pui, D., Mullholland, G. and N. Bryer, Use of the Electrostatic Classification Method to Size 0.1 µm SRM Particles – A Feasibility Study. Journal of NIST 96: 147, 1991.

Knutson, E. and K. Whitby, Aerosol Classification by Electric Mobility: Apparatus, Theory, and Applications. Journal of Aerosol Science, 6: 443-451, 1975.
Medved, A., Dorman, F., Kaufman, S.L. and A. Pöcher, A New Corona-based Charger for Aerosol Particles. Journal of Aerosol Science, 31:S616-S61, 2000.

Mullholand, G., Bryner, N. and C. Croarkin, Measurement of the 100 nm NIST SRM 1963 by Differential Mobility Analysis. Aerosol Science & Technology, 31: 39-55, 1999.

Oberdörster G, Oberdörster E and J. Oberdörster, Nanotoxicology: an emerging discipline evolving from studies of ultrafine particles. Environ Health Perspect, 11: 823-839, 2005.

Pourpix, M. and J. Daval, Electrostatic precipitation of aerosol on wafers, a new mobility spectrometer. In ‘Aerosols: Science, Industry, Health and Environment’, Pro. of the Third Int. Aerosol Conference, 24–27 Sept., 1990, Kyoto, Japan, Vol. II, edited by S. Masuda and K. Takahashi, Pergamon Press, 1990.

Sanchez V.C., Pietruska J.R., Miselis N.R., Hurt R.H., and A.B. Kane, Biopersistence and potential adverse health impacts of fibrous nanomaterials: What have we learned from asbestos? Wiley Interdiscip Rev Nanomed Nanobiotechnol., 1: 511-529, 2009.

Scheibel, H. G., and J. Porstendörfer, Generation of monodisperse Ag- and NaCl aerosols with particle diameters between 2 and 300 nm. Journal of Aerosol Science 14, 113-126, 1983.

TSI Inc., Generating Emery Oil Aerosol for Calibration. TSI Application note EM-004. TSI Inc., Shoreview, MN, USA. Available at http://www.tsi.com/uploadedFiles/ Site Root/Products/Literature/Application Notes/EM-004-Generating Emery Oil Aerosol-5001326A.pdf, 2006.

Zhang S.H., Akutsu Y., Russell L.M., Flagan R.C. and J.H. Seinfeld, Radial Differential Mobility Analyser. Aerosol Science & Technology, 23: 357-375, 1995.

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