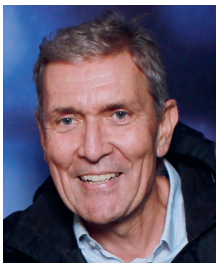
doi:10.2533/chimia.2026.13 Chimia 80 (2026) 13–20

Metrology of Nanoparticles

Oliver F. Bischof*, Heinz Burtscher, and Martin Fierz

Abstract: In the past decades, several measurement techniques have been developed and continuously optimized to specifically analyze airborne nanoparticles. Nanoparticles have gained significant importance in fields such as air quality research, climate studies, nanotechnology, material science, particle technology and filtration. Key measurement fundamentals for an accurate, reliable measurement of nanoparticles includes their sampling, conditioning, and analysis. We present a number of state-of-the-art aerosol measurement techniques, with a focus on condensation particle counters, mobility analyzers, and instruments based on the diffusion charging of particles. A brief overview of these methods is provided, with a special focus on work done in the framework of the ETH Nanoparticles Conference, which was originally founded to better understand and mitigate nanoparticles generated by vehicles and combustion processes.

Keywords: Characterization · Measurement methods · Nanoparticles · Physical properties



Oliver F. Bischof studied Chemical Engineering at TU Dresden where he developed his interest in particle research. He was a visiting student at Loughborough University in the UK as well as at Delft University in the Netherlands. He obtained his PhD from RWTH Aachen. Today, he is a senior director at TSI Incorporated and a guest researcher at the Institute of Climate and Energy Systems (ICE-3) at FZ Jülich.

Heinz Burtscher started his research work on aerosols at the laboratory for solid state physics of ETH with Prof. H. C. Siegmann. Then he became a scientist at the ABB research center in Dättwil working on electrostatic precipitators for coal fired power plants. At FHNW he founded the Institute for Aerosol- and Sensor Technology. His main areas of research are characterization of small particles, in particular combustion aerosols.

Martin Fierz has been developing nanoparticle detectors for 25 years, starting in Heinz Burtscher's research group at FHNW, and since 2012 also in the spinoff company naneos particle solutions that he co-founded.

1. Introduction

A very brief definition of nanoparticles and their main properties is given by Burtscher, this issue.[1] The measurement of aerosol particles consists of several steps:

- Sampling from ambient air or from an aerosol flow, for example exhaust gas.
- Conditioning steps such as dilution.
- The measurement itself, which may be *in situ* or for example analysis of a filter sample.

Here, only *in situ* techniques for physical particle properties of nanoparticles will be discussed. Techniques working in the aerosol phase (*in situ* techniques) avoid many artifacts and often allow a continuous measurement; however, they often yield only indirect results. For example, the light scattering of a particle is measured and then converted into a particle mass concentration.

The focus of this paper is on the measurement of nanoparticles, which is why optical methods (light scattering, absorption, and extinction) are not covered. As scattering for particles smaller than the wavelength of the light scales with d^6, and absorption with d^3, where d is the particle diameter, these techniques are insensitive to nanoparticles. Significant development of techniques based on particle charging has been done in Switzerland and regularly presented at the ETH nanoparticle conference. Therefore, more room is dedicated to this topic, including a short historical overview. The specific measurement of carbonaceous particles is discussed in Keller *et al.* in this issue.[2]

2. Sampling and Conditioning

In order to avoid particle losses due to impaction at the sampling location, the flow velocity in the sampling probe should match the external velocity. This is called isokinetic sampling and is particularly important for larger particles.[3] Several processes can lead to particle losses in a sampling system. Losses occur mainly by inertial impaction, diffusion, thermophoresis, and electrostatic deposition (Table 1). For accurate measurements, losses have to be minimized by optimizing the design of the sampling system.

Condensation or nucleation of volatile or semi-volatile material can have a great influence on the number concentration and size of submicrometer particles, for example when measuring hot exhaust gas. Supersaturation of volatile or semi-volatile material occurs when the exhaust gas cools down, which may lead to condensation on existing particles or formation of new particles by nucleation.[4] This can be controlled by removing the volatiles (using *e.g.* a thermodenuder[5] or catalytic stripper[6]), by keeping the temperature high enough or by dilution. Dilution may also be necessary because many instruments cannot handle high particle concentrations and to reduce soiling. A variety of dilution systems

*Correspondence: Dr. O. F. Bischof, E-mail: oliver.bischof@tsi.com
TSI, Aachen, Germany and Forschungszentrum Jülich ICE-3: Troposphere, Jülich, Germany

Table 1. Summary of mechanisms for particle loss or measurement bias

Mechanism for loss or bias	Effect	Counter measure
Non-isokinetic sampling	Potential over- or under-sampling	Isokinetic sampling
Inertial and gravitational deposition	Mainly important for micrometer-sized particles, small effect for particles <1µm in diameter	Avoid sharp bending (impaction) and long horizontal tubing (gravitational settling)
Diffusional deposition	Efficient for small particles, which contribute significantly to the number concentration, but usually negligible if mass is considered	Minimum tube length and/or high flow
Thermophor etic deposition	If the sampling line is much colder than the aerosol, particles are driven towards the wall	Heat sampling line, avoid high temperature gradients
Electrostatic deposition	If particles are charged, they may be attracted by electrostatically charged walls	Use electrically conductive tubing material (no Teflon!), no nonconducting surfaces

are available (*e.g.* dilution tunnel, ejector dilutor, rotating disk dilutor, see Dahal *et al.*[7])

3. Measurement Techniques

In order to characterize nanoparticles, the most common metric is the particle number concentration, often in addition to particle size information such as the average diameter or the size distribution. Another possibility is a more recently introduced metric called lung deposited surface area (LDSA[8]), which corresponds to the fraction of the particles' surface area concentration that would deposit in the alveolar or the tracheobronchial region of the human lung and therefore is said to offer the best correlation to several adverse health effects.[9]

Two main techniques are used to determine particle number. The first one is based on condensation particle counters (CPC) while the second one is based on charging the particles electrically with subsequent measurement of the electrical current in a diffusion charger device (DC), which is a technique that can also be applied to determine LDSA. Size information can be obtained by first determining the mobility of the particles (in a mobility analyzer), by diffusional separation (in a diffusion battery) or by utilizing their behavior in an accelerated gas flow (in cascade impactors or aerodynamic particle sizers, although these only start measuring at 500 nm).

3.1 *Condensation Particle Counters (CPC)*

The most frequently used instrument to determine the number concentration of airborne particles is the CPC, which dates back to 1890 when John Aitken[10] first described experiments with a simple expansion-type condensation nucleus counter. The operational principle of most contemporary CPCs stems from the work of Bricard and coworkers[11] and the instrument design of Agarwal *et al.*[12] Today, there are several types of CPCs available that differ based on the working fluid they use or on their flow regime. The most common working fluids are butanol, isopropanol, and distilled water, although more recently diethylene glycol, propylene glycol and dimethyl sulfoxide[13] have also been used. The majority of the CPCs in use today are continuous laminar-flow instruments, even though adiabatic-expansion-type instruments as well as mixing-type designs[14] continue to exist. What all of these CPCs have in common is that they measure the particle number concentration over a very wide size range, covering an aerosol's nucleation mode, its Aitken mode, as well as its accumulation mode (definitions see Ref. [1]), *i.e.* from a few nanometers to a few micrometers.

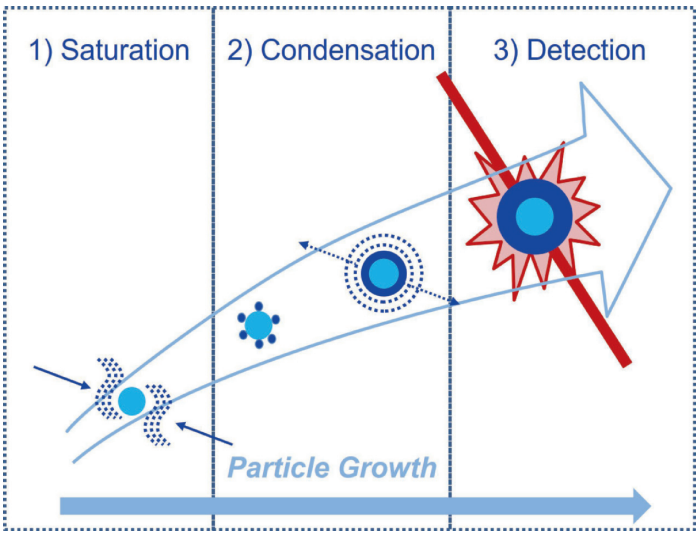


Fig. 1. Basic operational principle of a CPC.[17]

In any CPC, the particles are first guided through an environment of saturated vapor that is formed from the working fluid. When that vapor becomes supersaturated, it condenses onto the particles, which makes them grow from their original size to droplets of a few micrometers that can then be easily detected optically,[3,15] see Fig. 1. The diameter where the counting efficiency is 50% is called the lower cut-off diameter. In all CPCs that use an alcohol as the working fluid, the vapor is first heated and then cooled to achieve super-saturation. This is different in modern water-based CPCs, where the temperatures have been inverted so that condensation of the water vapor onto the particles occurs in a growth tube with wetted walls that is warmer than the sample flow.[16]

In an ideal instrument, the counting efficiency would be 100% for all particle sizes, but in reality it drops rapidly at smaller particle sizes as the required supersaturation increases with decreasing diameter due to the Kelvin effect.[3] The lowest particle size that CPCs can detect starts at roughly 1.5 nm, with 10 nm being the most common cut-off size, and the largest size is typically 3 to 5 micrometers in diameter. It should be noted that errors during the measurement of very small particles are likely to occur due to diffusion losses in the entire measurement system. CPCs in counting mode allow a very high measurement accuracy of typically ±10%, and even down to ±5%, independently of the parameters of the optical system. CPCs are able to measure low concentrations very accurately, even at cleanroom levels, but may suffer from undercounting at high concentrations when particle coincidence starts to take place. This phenomenon occurs when more than one particle is present in the detection volume at the same time and it will typically happen between 10,000 and 100,000 P/cm^3, depending on the CPC design.

3.2 *Mobility Analysis*

Mobility analysis, or more specifically electrical mobility analysis, is the most frequently used technique to determine the

size distribution of submicrometer particles, *i.e.* from about 1 nm up to 1 μm in diameter. The individual electrical mobility of the particles is determined by their drift in an electrical field. In this case the electrical mobility b_{el}.

$$b_{el} = b \cdot q \quad (1)$$

is the key metric, where b is the mobility[1] and q the particle charge. The particle size can then be calculated from b_{el} if the particle charge is known, which is established by first charging the particles with a high concentration of bipolar ions to their well-defined steady state charge equilibrium (which is commonly referred to as their Boltzmann equilibrium). This step takes place in a bipolar diffusion charging device[3] that contains a radioactive or a soft X-ray source. Ideally, particles should carry only one elemental charge, which is predominately the case for nanoparticles below 100 nm. A correction for multiple charging effects becomes necessary for larger particles. The charged particles then pass into a differential mobility analyzer[18] (DMA), which classifies the particles according to their electrical mobility. Today, DMAs exist in a number of different forms, including cylindrical, radial, and high-flow designs. The most common DMA type is the cylindrical DMA as shown in Fig. 2, which consists of two concentric cylinders, of which the inner one is an electrode to which a controlled high voltage is applied.

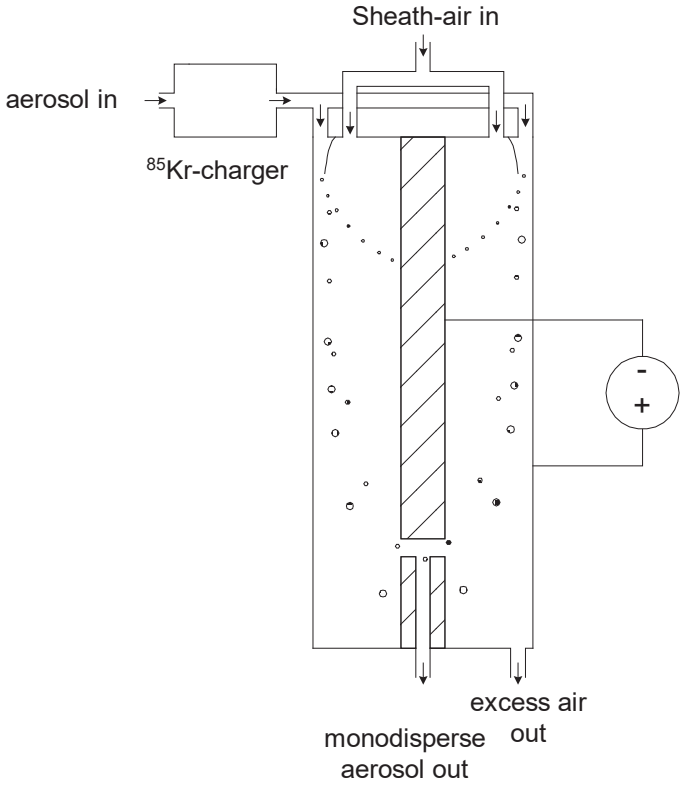


Fig. 2. Basic operational principle of a differential mobility analyzer.[15]

The center rod is surrounded by a flow of filtered, particle-free sheath air. In the design shown in Fig. 2, the sample flow is introduced at the top of the DMA and flows down laminarly with no mixing of the two flows. The positively charged particles that enter the annular space between the cylinders are attracted through the sheath air to the center electrode when a negative voltage is applied. The smallest-sized particles reach the center column first and are deposited there, while the largest particles leave the DMA with its excess air flow. At a given voltage, particles of one defined electrical mobility and thus particle size are steered into a small extraction slit at the bottom of the electrode and subsequently exit through the outlet as monodisperse aerosol. The sample flow can then be size-classified by varying the voltage on the electrode successively. The size classification of particles by a DMA can be very accurate with a relative error of only 0.1 % for 100 nm particles,[19] although that accuracy will decrease the larger the particles are due to the presence of multiple charges.

After the particles have been size-classified, their number concentration can be measured for each size class. This is usually done with a CPC, although aerosol electrometers can also be used. The complete measurement of particle size distributions based on first size classifying and then counting particles can be conducted in a discontinuous, stepping mode or in a faster scanning mode. In both modes, a computer controls the DMA flows and voltage as well as the CPC. It also collects the data and calculates the resulting particle size distribution with a resolution of 160 or more size classes. The discontinuous mode of a differential mobility particle sizer (DMPS) takes about 20 min for a complete run. In a scanning mobility particle sizer[20] (SMPS), the DMA voltage is scanned in a continuous ramp rather than in discrete steps. It is important that during the scan the size distribution is constant. In modern SMPS spectrometers, this reduces the time required to measure complete size distributions of nanoparticles to about 30 to 60 seconds (depending on concentration and precision required). Due to the much faster scan, the SMPS is extensively used. Care has to be taken to choose the correct scanning time as the size spectrum can get distorted if it is too fast.[21] The minimum possible scanning time without incurring distortion of the measured distribution depends on the CPC's response time.

A time resolution of one minute or less using SMPS mode allows a quasi-transient measurement. Higher time resolutions can be achieved by a design having a series of detection electrodes, where the current of charged particles arriving at the electrode is measured (Fast Mobility Particle Sizer (FMPS), EEPS by TSI, Cambustion DMS500). This allows a parallel measurement of several size classes instead of scanning.[22] If operated at very high flow rates, even particles below 1 nm can be measured by mobility analysis.[23]

3.3 *Size Classification by Diffusion*

The fundamental technique of a size separation by diffusion, originally to classify gas molecules based on their diffusion rate, goes back to Townsend.[24] It took another dozen years or so until Millikan and Fletcher first used it with airborne particles. In essence, this technique relies on the inverse relationship between the size of a nanoparticle and its mechanical mobility while it is subjected to diffusion. A particle's mechanical mobility b and the diffusion coefficient D are related by the Einstein relation

$$D = kT \cdot b \quad (2)$$

This means that mobility analysis and diffusion analysis yield the same information, the 'mobility diameter'.[1] By diffusion, particles may reach the wall of a confinement (for example a tube) and be precipitated there. For smaller particles, having a high diffusion constant, this process will be faster. Diffusion is thus an effective mechanism to segregate very small particles, as the smaller the particle, the higher the probability for it to be deposited on the wall of a tube or on the mesh of a screen. When an aerosol sample passes through a series of diffusion stages, it allows the determination of particle size distributions by measuring the subsequent reduction in the total concentration of the aerosol.

Diffusion losses and thus particle penetration are independent of the tube diameter. Bundles of tubes can be combined to build

a diffusion battery. As diffusion is strong for very small particles, this method is especially useful to analyze particles <300 nm. Besides tubes, other configurations can be used.[3] The development of multi-stage, screen-type diffusion batteries can be attributed to Sinclair,[25] which is the design that was later adopted in the first commercial Diffusional Particle Sizer (DPS) system made by TSI Incorporated.[26] It consisted of ten stages, with the first stage having one diffusion screen and each of the successive stages containing an increasing number of screens. The first stage removed a large amount of the nanoparticles and each subsequent stage a fraction of slightly larger particles. In a DPS measurement system, the diffusion battery acted as a classifier that sent the particles *via* a switching valve to a continuous-flow CPC that then determined the particle number concentration of a certain size fraction. This measurement technique worked well for particles as small as 2 nm but had an upper limit of about 200 nm.

The limited size range, the low size resolution and also the ill-posed data inversion, which frequently resulted in large and unstable changes in the particle size distribution, led to the abandonment of this measurement technique in favor of electrical mobility measurements in the mid-1990s. In 2002 Fierz *et al.*[27] introduced the electrical diffusion battery (EDB). While the original EDB did not survive as a commercial product, it ultimately led to the development of the miniature diffusion size classifier (miniDiSC), based on diffusion charging, and later on the Partector instruments.

3.4 *Sensors Based on Diffusion Charging*

3.4.1 *A Short Overview of the History of Diffusion-charging Based Instruments from Switzerland*

Many nanoparticle instruments based on diffusion charging have been invented and built in Switzerland. The history of these developments originates with Prof. H. C. Siegmann of ETH Zurich. He started measuring air pollution in 1958 while in Munich, when his advisor Walter Gerlach asked him to investigate whether he could detect radioactivity in the air originating from atomic bomb testing by measuring air conductivity. While this failed, Siegmann found that one could measure particulate air pollution instead. He retained his interest in air pollution and its measurement over his entire career and the basis for all instruments described here was laid in his research group at ETH. Early efforts were based on the photoelectric charging of particles (see Keller *et al.*[2]) and subsequent electrical current measurements, whereas later, diffusion charging became more important. There, a corona discharge produces unipolar ions that are mixed with the aerosol, thus charging the particles. The signal of a DC sensor depends on the particle diameter and concentration. Attempts to 'market' this signal as a relevant property by linking it to 'active surface area' (AS) or 'lung-deposited surface area' (LDSA) both largely failed, as customers were looking for more easily comprehensible metrics such as mass concentration or particle number. The simple instruments measuring the charging alone *via* a single current measurement were rather unsuccessful in the market.

3.4.2 *Obtaining Size Information and Particle Number by Diffusion Charging Based Instruments*

As Prof. Siegmann reached retirement age and his research group at ETH was dissolved, a former member of his lab, Prof. Heinz Burtscher started to continue development of aerosol instruments at the Fachhochschule Aargau, later Fachhochschule Nordwestschweiz (FHNW). The first instrument to be developed there was the electrical diffusion battery (EDB[27]), based on a patent by Burtscher and Siegmann. This instrument, an extension of the simple diffusion charger, used multiple electrometer stages with metallic grids to first capture particles by diffusion, followed by a filter to collect all particles that got through all diffusion stages. The EDB could resolve different size fractions of the aerosol and thus measure rough particle size distributions (and therefore also particle number) with high time resolution.

A simplified version with only a single diffusion stage followed by a filter stage was the next step, again at FHNW: the Diffusion Size Classifier (DiSC[28]). With only two signals to analyze, it could no longer measure particle size distributions, but could still estimate an average particle diameter and particle number. This battery-powered instrument was commercialized by Matter Aerosol AG.

A noteworthy innovation in the DiSC was a completely empty first detection stage ('induction stage') which unlike the other stages that measured the charge deposited by the particles as electric current - could sense only the rate of change of the amount of charge within the stage (Fig. 3). This induction stage was used to compensate for space-charge effects due to rapidly changing aerosol concentrations that distorted the signals in the diffusion stage and was to become important on its own later.

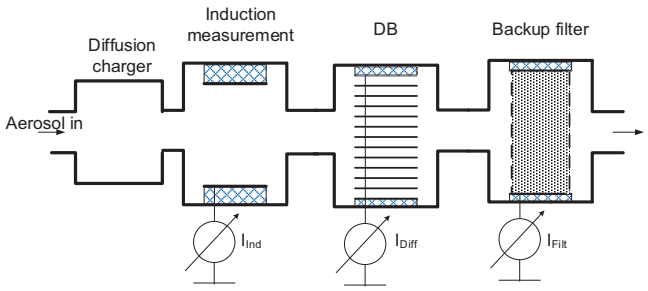


Fig. 3. Setup of the Diffusion Size Classifier.

Finally, in 2007, a miniaturized version of the DiSC, the miniDiSC[29] was developed at FHNW. Following its commercialization (again by Matter Aerosol), it was one of the first truly handheld and portable aerosol detectors available and was the first of all the diffusion charging-based instruments described here to attain commercial success.

3.4.3 *Instruments Using Induced Current Detection*

In 2006, Burtscher and Schmidt-Ott recognized the potential of the induced current detection technique pioneered in the DiSC and patented a new method to measure particle number concentrations. It was based on continuous aerosol charging, followed by pulsed partial precipitation of the particles in an electric field. The periodic change in charge was to be measured in an induction stage as in the DiSC. Burtscher and Schmidt-Ott showed that the signal amplitude in the induction stage was directly proportional to the particle number concentration (but gave no further information, *e.g.* on average particle size as in the DiSC). This elegant idea was, however, not realized in a commercial instrument until the patent expired about 10 years later.

The big advantage of using an induction stage is that it produces an AC (alternating current) signal at a frequency of typically about 1Hz. The amplitude of this AC signal is measured and is not affected by any much slower-varying zero offset drift of the electrometers. The electrometer offset drift was an issue that plagued all previous instruments that measured direct current signals. These instruments had to be heated to a defined temperature to reduce zero offset drifts, which required warmup times, and the heating used a lot of power, reducing battery lifetime. Even with the heating, changes in humidity could still cause zero offset drifts, therefore using AC signals instead led to much more robust measurements.

The first instrument to actually apply the idea of measuring aerosols by only induced currents was developed once again at

FHNW in 2011. It was commercialized as the Partector by a new spinoff company, naneos, in 2012.[30] The Partector (Fig. 4) was again a handheld instrument, even smaller than the miniDiSC, and because it only had a single detection stage, it could once more only detect the total charge on the aerosol, interpreted as LDSA. Even though it was much more advanced than the original DC sensors (smaller, lighter, cheaper, more robust) it again struggled to find a market niche due to the unusual metric LDSA, which could not be calibrated against a reference instrument.

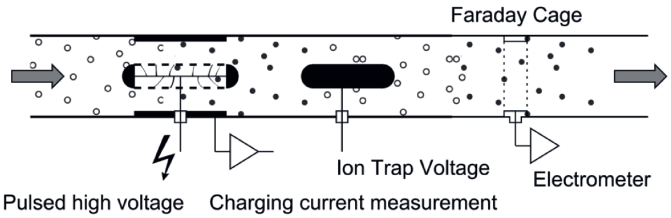


Fig. 4. Setup of the Partector.

However, the long elusive commercial success finally came with the introduction of new regulations for type approval of cars in the EU: following Dieselgate. The EU demanded that the particle emissions of diesel vehicles be measured not only on test benches, but also in real-world driving with particle number counting portable emissions measurement systems (PN-PEMS). While the particle number emissions could easily be measured by condensation particle counters (CPC) in a laboratory-like setup of the vehicle test bench, it was much harder for these instruments to deal with accelerations, power limitations and the generally less controlled on-road environment during on-road test. In 2015, the Austrian company AVL, a market leader in emissions testing, asked naneos to develop a diffusion charging-based particle number measuring sensor. Since the patent holder of Burtscher and Schmidt-Ott's elegant particle number sensor had just let the patent expire, naneos developed the 'automotive partector' in collaboration with FHNW (Fig. 5).

Fig. 5. A PN-PEMS based on the automotive Partector. Picture © AVL List GmbH.

Thanks to AVL's standing in the emissions testing market, the AVL PN-PEMS, based on the automotive partector became successful in the market, and crucially paved the way for DC-based particle number counting technology in the automotive industry.

In 2018, another collaboration between naneos and FHNW produced the Partector 2 (see Fig. 6), a dual-stage instrument similar to the (mini)DiSC (Fig. 4). Instead of using the size dependent diffusion coefficient for particle sizing, the Partector 2 uses an electrostatic precipitator between two induction stages. The first stage measures the total current as in the Partector, whereas the second stage measures a reduced current since a fraction of the particles has been removed in the precipitator.

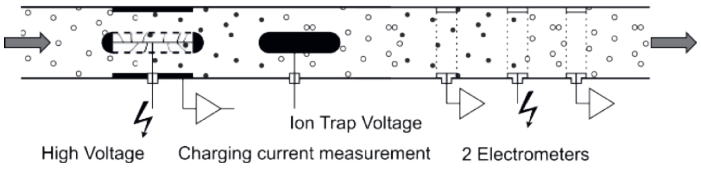


Fig. 6. Partector 2.

The Partector 2 is even smaller and lighter than the miniDiSC and has a much longer battery life – both partially made possible because the AC detection principle needs no more heating. Furthermore, unlike the fixed deposition characteristics of the diffusion stage in the miniDiSC that are given by geometry and flow rate, the voltage of the electrostatic precipitator can be changed to either adapt the detectable size range of the measured particles, or to measure multiple signals on the second induction stage at different precipitator voltages. In this final version, the Partector 2 Pro, developed by naneos, the Swiss instrument development has come full circle – back to the detection of rough particle size distributions as in the EDB – only this time in a miniature and battery-powered instrument, at a much lower price. Of course, compared to the reference instrument for measuring particle size distributions, the scanning mobility particle sizer (SMPS), the Partector 2 Pro has a much coarser size resolution – but for many applications its small size, low weight, and ease of use more than compensates for the lower measurement accuracy. A comparison of other DC-based instruments can be found in Ref. [31].

3.4.4 *Legacy: 10,000s of DC-based Instruments in Europe in 2025*

The successful first application of DC-based instruments for particle number concentration measurements in vehicle emissions mentioned above soon led to the extremely widespread adoption of DC-based instruments in a much larger market: It became increasingly clear that the theoretically extremely effective diesel particle filters (DPF) used in millions of vehicles were prone to failure, and since the early 2020s an increasing number of European countries (the Netherlands, Belgium, Germany, Switzerland, Spain as of 2026) has mandated the testing of DPF during periodic inspection. Unlike type approval, this market demanded much cheaper instruments that every workshop could buy. As a result, the simpler DC-based instruments have outcompeted the CPC-based solutions in this market. About a dozen different DC-based instrument types are now being sold to detect defective DPF and improve air quality. Tens of thousands of these instruments are now in use in Europe – and many of them are either clones of the instruments developed in Switzerland (in particular, the miniDiSC and the automotive Partector), or are based on similar ideas. And all of this began over 65 years ago with Walter Gerlach's concern over radioactivity due to atomic bomb testing!

3.5 *Low Pressure Impactor*

In an impactor the aerosol is passed through a nozzle and directed towards an impaction plate, deflecting the gas flow. Due to their inertia particles do not immediately follow this deflection and may hit the impaction plate, depending on their aerodynamic diameter.[1,3] Cascade impactors operating close to ambient pressure cannot be used to measure nanoparticles. However, at reduced pressure this becomes possible, if operated in a supersonic mode below 1 nanometer.[32] The only commercial device making use of low pressures and allowing *in situ* operation is the Electrical Low Pressure Impactor[33] (ELPI). Particles are charged by a corona charger and subsequently precipitated in 14 stages (=size fractions from 6 nm to 10 µm) of a cascade impactor. The current, produced by the precipitated particles, is measured, and used to determine the concentration in the corresponding size class.

3.6 *Summarizing Tables*

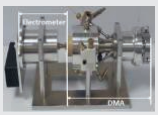
As different processes (*e.g.* diffusion and impaction) dominate in certain size ranges, no instrument exists which can cover the whole size range of interest. Results from different systems have to be combined to obtain site distributions over a large size range. As they measure different particle properties (such as mobility, light scattering) it is often not straightforward to combine the results. Fig. 7 shows the size range covered by different techniques. In Table 2, a selection of common commercial devices is shown. Information on calibration and traceability can be found in Vasilatou *et al*.[34]

4. Outlook and Future Trends

Laboratory instrumentation to characterize nanoparticles has existed for a long time. However, only in the past two decades have the first regulations been established that require the measurement of nanoparticles. This has led to the development of more affordable and easier to use devices.

It all started with the plans for a new railway link through the Alps, a 50 km tunnel in Switzerland. The need to achieve acceptable air quality during the tunnel construction lead to the formation of the VERT consortium (Verminderung der Emissionen von Realmaschinen im Tunnelbau), which demonstrated that filtration efficiencies of 99% and higher for nanoparticles by their number concentration could be achieved.[36] This effort eventually resulted in the foundation of the Particle Measuring Program (PMP) to establish a procedure for the type approval test for particulate emissions from diesel engines, and ultimately the Euro 5b standard for light-duty diesel passenger cars that enforced a particle number limit of 6×10^{11} P/km in 2011. This first particle number standard was followed by equivalent emission standards for gasoline vehicles, heavy-duty diesel vehicles, off-road construction machinery

Table 2. Selection of commercial devices for nanoparticle measurements, and summary of their main characteristics (adapted from Pelzer *et al*., 2010[35])

Device name	Scanning Mobility Particle Sizer™ (SMPS™)	Fast Mobility Particle Sizer™ (FMPS™)	Half Mini (m) model Differential Mobility Analyzer	Electrical Low Pressure Impactor (ELPI®+)	Partector 2 Pro	MiniWRAS 1371 Portable wide-range aerosol spectrometer
Particle size information	Size distribution	Size distribution	Size distribution	Size distribution	Size distribution, average size	Size distribution
Photo						
Physical measuring principle	Bipolar neutralization, electrical mobility classification and detection with condensation particle counter	Unipolar electrical charging, electrical mobility classification and detection with aerosol electrometers	Electrospray ionization, mobility classification, detection by aerosol electrometer	Charging of particles, size classification in a cascade impactor and detection with aerosol electrometers	Diffusion charging (DC), electrical mobility-based sizing	Diffusion charging (DC), electrical mobility-based sizing and optical particle counting
Measuring range (particle size) in nm	1.5 to 1,000 depending on configuration	5.6 to 560	1 to 30	6 to 10,000	10 to 300	10 to 193 el. 253 to 35×10^3 opt.
Measuring range, (concentration) in P/cm^3	1 to 10^8, depending on model	approx. 300 to 5×10^6	not specified	approx. 150 to 10^7, depending on size	PN: 0 to 10^6 LDSA: 0 to 12× 10^4 µm²/cm³	10^2 to 10^6 el. 0 to 5.3×10^3 opt.
Measuring accuracy (factory calibration)	Size: typically < ± 5 %, Number concentration: typically ± 10 %	not specified	Size: at 2 nm ±3% Number not specified	size-dependent, approx. 10 #/cm^3 for 100 nm particles	typically ± 30 %	typically ± 40 %
Total number of channels less than 100 nm	up to 167 up to 128	32 20	not specified	14 4	8 8	10 el. 31 opt. 8
Time resolution in s	20 to 300	1	2	0.1	1 scanning 6	60 el. 6 opt.
Stationary/ portable	stationary	stationary	stationary	stationary	portable	portable
Manufacturer	TSI Incorporated	TSI Incorporated	SEADM	Dekati Ltd.	naneos	Grimm

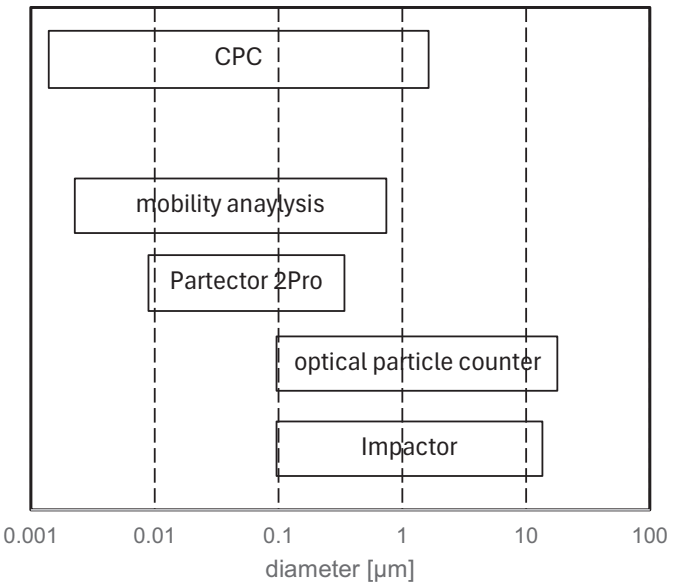


Fig. 7. Size range where different instruments can be used.

and also aircraft.[37] In addition, there are also standards for on-road vehicle tests with portable emission measurement systems to determine the number of nanoparticles emitted under real-driving conditions today (PN-PEMS).

More recently, an exhaust measurement based on the particle number concentration was introduced as part of the periodical technical inspection (PTI) of diesel vehicles in B, NL, GER and CH.[38] This standard drove the development of a whole suite of new instruments capable of measuring nanoparticles at a much lower price, which became the first mass market for aerosol instruments. As a next step, PTI is expected to be extended to gasoline engines. The higher content of volatiles and water leads to different requirements, instrument specifications as well as operation conditions still have to be defined.[39]

In parallel, activities on the ambient air side have likewise gained momentum. In 2021, the World Health Organization (WHO[40]) published their global air quality guidelines, which contained a good practice statement on ultrafine particles to guide authorities to reduce ambient concentrations. This led to the New EU Ambient Air Quality Directive, that was approved by the EU Council in October 2024, which set stricter AQ (air quality) standards for pollutants that expanded the scope of ambient AQ monitoring. EU member states are required to incorporate metrics for nanoparticle number and size distributions into local AQ monitoring networks, with a goal of meeting them by 2030. In the near future (within the next five years) we will see particle number measurements of vehicles as part of their PTI rolled out in many more countries, the creation of more AQ monitoring stations (one per 5 million inhabitants is currently required in the EU), mandatory measurements at locations where high concentrations of ultrafine particles are likely to occur as well as an increased use of lower-cost nanoparticle devices to complement regulated activities.

The need to shift the detection limit to ever smaller sizes and to achieve a wide concentration range requires the optimization of existing technologies or to develop new ones.

Competing interests

Oliver F. Bischof is a full-time employee of TSI GmbH, a subsidiary of TSI Incorporated, which manufactures several instruments described in the paper. Martin Fierz is the co-founder and CEO of naneos particle solutions gmbh, manufacturer of the Partector 2 Pro and further DC-based instruments.

Received: October 23, 2025

[1] H. Burtscher, *CHIMIA*, **2026**, *80*, 8, https://doi.org/10.2533/chimia.2026.8.
[2] A. Keller, H. Burtscher, E. Weingarnter, *CHIMIA*, **2026**, *80*, 21, https://doi.org/10.2533/chimia.2026.21.
[3] W. C. Hinds. Aerosol Technology, J. Wiley & Sons, New York, **1999**.
[4] H. Burtscher, *J. Aerosol. Sci*. **2005**, *36*, 896, https://doi.org/10.1016/j.jaerosci.2004.12.001.
[5] H. Burtscher, U. Baltensperger, N. Bukowiecki, C. Hüglin, M. Mohr, U. Matter, S. Nyeki, N. Streit, E. Weingartner, *J. Aerosol Sci.* **2001**, *32*, 427, https://doi.org/10.1016/S0021-8502(00)00089-6.
[6] B. Giechaskiel, A.D. Melas, T. Lähde, G. Martini, *Vehicles* **2020**, *2*, 342, https://doi.org/10.3390/vehicles2020019.
[7] K. Dahal, P. Kubesa, H. Hartmann, I. Fraboulet, Technical Report, **2023**, Kuopio, Finland, https://doi.org/10.13140/RG.2.2.19178.08642.
[8] H. Fissan, S. Neumann, A. Trampe, A. D. Y. H. Pui, W. G. Shin, *J. Nanopart. Res.* **2007**, *9*, 53, https://doi.org/10.1007/s11051-006-9156-8.
[9] G. Oberdörster, *Int. Arch. Occup. Environ. Health* **2001** *74*,1, https://doi.org/10.1007/s004200000185.
[10] J. Aitken, *Proc. R. Soc. Edinburgh*, **1890**-**1891**, XVII, 39-53.
[11] J. P. G. M. Bricard, P. Delattre, G. Madelaine, M. Pourprix, 'Fine particles' ed. B.Y.H. Liu, Academic Press, New York, **1976**, 565-580.
[12] J-K. Agarwal, G. J. Sem, *J. Aerosol Sci.* **1980**, *11*, 343, https://doi.org/10.1016/0021-8502(80)90042-7.
[13] P. Weber, O. F. Bischof, B. Fischer, M. Berg, J. Schmitt, G. Steiner, L. Keck, A. Petzold, U. Bundke, *Aerosol Res.* **2023**, *1*, 1, https://doi.org/10.5194/ar-1-1-2023.
[14] Y. Kousaka, T. Niida, K. Okuyama, H. Tanaka, *J. Aerosol Sci*. **1982**, *13*, 231, https://doi.org/10.1016/0021-8502(82)90064-7.
[15] P. Kulkarni, P. A. Baron, K. Willeke, 'Aerosol Measurement, Principles, Techniques and Applications', John Wiley & Sons, **2011**.
[16] S. V. Hering, M. R. Stolzenburg, F. R. Quant, D. R. Oberreit, P. B. Keady, *Aerosol Sci. Technol*. **2005**, *39*, 659, https://doi.org/10.1080/02786820500182123.
[17] O. F. Bischof, 'Schriften des Forschungszentrums Jülich, Energy & Environment' **2022**, 579, ISBN 978-3-95806-629-8.
[18] E. O. Knutson, K. T. Whitby, *J. Aerosol Sci*. **1975**, *6*, 443, https://doi.org/10.1016/0021-8502(75)90060-9.
[19] P. D. Kinney, D. Y. Pui, G. W. Mulholland, N. P. Bryner, *J. Res. Nat. Inst. Stand. Technol*. **1991**, *96*, 147, http://doi.org/10.6028/jres.096.006.
[20] A. Tröstl, T. Tritscher, O. F. Bischof, H.-G. Horn, T. J. Krinke, U. Baltensperger, M. Gysel, *J. Aerosol Sci*. **2015**, *87*, 75, https://doi.org/10.1016/j.jaerosci.2015.04.001.
[21] S. C. Wang, R. C. Flagan, *Aerosol Sci. Technol*. **1990**, *13*, 230, https://doi.org/10.1080/02786829008959441.
[22] T. A. Sipkens, A. Boies, J. C. Corbin, R. K. Chakrabarty, J. Olfert, S. N. Rogak, *J. Aerosol Sci*. **2023**, *173*, 106211, https://doi.org/10.1016/j.jaerosci.2023.106211.
[23] L. J. Perez-Lorenzo, V. Khanna, T. Meena, J. J. Schmitt, J. Fernandez de la Mora, *Aerosol Sci. Technol*. **2020**, *54*, 128, https://doi.org/10.1080/02786826.2019.1684433.
[24] J. S. Townsend, *Philos. Trans. R. Soc., A* **1900**, *193*, 129, https://doi.org/10.1098/rsta.1900.0004.
[25] D. Sinclair, Proc. 7th Conference on Condensation and Ice Nuclei, **1969**, 132.
[26] R. J. Remiarz, G. J. Sem, J. K. Agarwal, C. E. McManus, TSI Quarterly, **1980**, *6*, 5, a publication of TSI Incorporated, St. Paul, MN.
[27] M. Fierz, L. Scherrer, H. Burtscher, *J. Aerosol Sci*. **2002**, *33*, 1049, https://doi.org/10.1016/S0021-8502(02)00057-5.
[28] M. Fierz, H. Burtscher, P. Steigmeier, M. Kasper, SAE 2008-01-1179, https://doi.org/10.4271/2008-01-1179.
[29] M. Fierz, C. Houle, P. Steigmeier, H. Burtscher, *Aerosol Sci. Technol*. **2011**, *45*, 1, https://doi.org/10.1080/02786826.2010.516283.
[30] M. Fierz, D. Meier, P. Steigmeier, H. Burtscher, *Aerosol Sci. Technol*. **2014**, *48*, 350, https://doi.org/10.1080/02786826.2013.87598.
[31] Ch. Asbach, H. Kaminski, D. von Barany, T. A. J. Kuhlbusch, Ch. Monz, N. Dziurowitz, J. Pelzer, K. Vossen, K. Berlin, S. Dietrich, U. Götz, H.-J. Kiesling, R. Schierl, D. Dahmann, *Ann. Occup. Hyg*. **2012**, *56*, 606, https://doi.org/10.1093/annhyg/mes033.
[32] J. F. De la Mora, S. V. Hering, N. Rao, P. H. McMurry, *J. Aerosol Sci*. **1990**, *21*, 169, https://doi.org/10.1016/0021-8502(90)90002-F.
[33] S. Saari, A. Arffman, J. Harra, T. Rönkkö, J. Keskinen, *Aerosol Sci. Technol*. **2018**, *52*, 1037, https://doi.org/10.1080/02786826.2018.1500679.
[34] K. Vasilatou, K. Iida, M. Kazemimanesh, J. Olfert, H. Sakurai, T. A. Sipkens, G. J. Smallwood, *J. Aerosol Sci*. **2025**, *183*, 106483, https://doi.org/10.1016/j.jaerosci.2024.106483.
[35] J. Pelzer, O. F. Bischof, W. van den Brink, M. Fierz, H. Isherwood, H. Gnewuch, A. Knecht, T. Krinke, A. Zerrath, *Gefahrstoffe – Reinhalt. Luft*, **2010**, *70*, 469.
[36] A. Mayer, J. Czerwinski, U. Matter, M. Wyser, D. Kieser, *SAE Technical Paper* **1998**, 980539, https://doi.org/10.4271/980539.
[37] O. F. Bischof, *Emiss. Control Sci. Technol*. **2015**, 1, 203, https://doi.org/10.1007/s40825-015-0016-9.

[38] A. Mayer, J. Czerwinski, T. Lutz, F. Legerer, M. Wyser, P. Comte, L. Larsen, L. Rubino, K. Vasilatou, D. Engelmann, M. Knoll, H. Burtscher, *Emiss. Control Sci. Technol.* **2025**, *11*, 7, https://doi.org/10.1007/s40825-024-00257-0.
[39] A. Melas, J. Franzetti, R. Suarez-Bertoa, B. Giechaskiel, *Sensors* **2024**, *24*, 6509, https://doi.org/10.3390/s24206509.
[40] WHO global air quality guidelines, Geneva, World Health Organization, **2021**. ISBN-13: 978-92-4-003421-1

License and Terms

The definitive version of this article is the electronic one that can be found at https://doi.org/10.2533/chimia.2026.13