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Performance study of portable devices for the real-time measurement of airborne particle number concentration and size (distribution)

Sébastien Bau[1], Raphaël Payet[1], Olivier Witschger[1] and Elżbieta Jankowska[2]

[1]Institut National de Recherche et de Sécurité (INRS), Laboratoire de Métrologie des Aérosols, Rue du Morvan, CS 60027, F 54519 Vandoeuvre Cedex, France;

[2]Central Institute for Labour Protection (CIOP-PIB), Department of Chemical, Aerosol and Biological Hazards, PL 00-701 Warsaw, Poland

E-mail: sebastien.bau@inrs.fr

Abstract. The aim of this experimental study was to investigate the performance of both portable and transportable devices devoted to the real-time measurement of airborne particle number concentration and size (distribution). Electrical mobility spectrometers (SMPS, FMPS, Nanoscan) as well as diffusion chargers (DiSCmini, Nanotracer) were studied. Both monodisperse and polydisperse aerosols were produced within the CAIMAN facility to challenge the instruments. The monodisperse test aerosols were selected in the 15-400 nm diameter range using a differential mobility analyser (DMA), and presented number concentrations of between 6.10^2 and 2.10^5 cm^{-3}. The polydisperse test aerosols presented modal diameters of between 8 and 270 nm and number concentrations between 4.10^3 to 10^6 cm^{-3}. The behavior of the different devices is expressed as (1) the ratio of the reported diameter to the reference diameter, and (2) the ratio of the reported number concentration to the reference concentration. These results are displayed as boxplots to better represent the statistical distribution of the experimental results. For the group of electrical mobility spectrometers, a good agreement between SMPS and FMPS and the reference was demonstrated. A slight tendency for the Nanoscan to underestimate particle size distribution for particles above around 100 nm was observed. The data reported for the group of diffusion chargers demonstrate that all, except the Nanotracer, show a tendency to underestimate particle diameter, by a factor around -40% to -10%. In the case of particle concentration, larger deviations were observed.

1. Introduction

Nanomaterials have been increasingly developed and used in many technology and industry sectors over the last 20 years, and increasing numbers of workers are thus likely exposed to airborne nanoparticles [1]. The parameters that should be assessed in order to characterize airborne nanomaterials are still being debated, and implementation of a multi-metric approach has recently been suggested [2-4].

In addition to chemical composition, airborne particle number concentration as well as particle size are among the parameters of interest [5] as they allow determination of the nanoparticle quantity and indicate the region of the respiratory tract where inhaled nanoparticles will be deposited and potentially interact. Methodologies to assess occupational inhalation exposure to airborne particles during production, handling and use of manufactured nanomaterials have recently been proposed [6-12] and tested in various workplace environments [13-18]. In particular, these strategies emphasize the utility of real-time instruments.

Investigating the performances of instruments devoted to the measurement of airborne nanoparticles is crucial prior to their use in workplaces, e.g. [19, 20]. Both “gold-standard” instruments, such as electrical mobility analyzers (e.g., Scanning Mobility Particle Sizer – SMPS, Fast Mobility Particle Sizer – FMPS, Nanoscan – NS), and portable and battery-operated diffusion chargers, designed for occupational hygiene/workplace exposure monitoring, are studied in this work.

It is also expected that this work will feed into the standardization work currently underway in Working Group 3 of CEN/TC137 (Assessment of workplace exposure to chemical and biological agents - Particulate matter) [21, 22].

2. Materials and methods

2.1. Test aerosols

Both monodisperse and polydisperse test aerosols, consisting of metals (carbon, titanium, silver), metal alloy (constantan), salts (sodium chloride, cesium chloride) and organic compounds (DEHS – DiEthylHexylSebacate), were produced to challenge the instruments. All aerosols were produced within the CAIMAN facility developed at INRS [23]. The monodisperse aerosols consisted of originally polydisperse aerosols, which were subsequently DMA-selected. The range of particle (modal) diameter and number concentration for both monodisperse and polydisperse test aerosols are presented in Table 1.

Table 1. Range of modal diameters and number concentrations investigated.

	Range of (modal) diameter (nm)	Range of number concentration (cm^{-3})
monodisperse	15 – 400	$6.10^2 – 2.10^5$
polydisperse	8 – 270	$4.10^3 – 1.10^6$

Examples of monodisperse and polydisperse number size distributions of the test aerosols are shown in Figures 1 and 2.

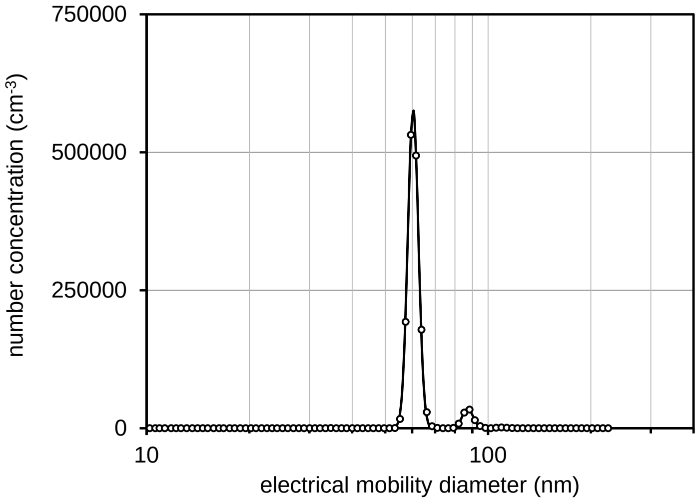

Figure 1. Example of monodisperse number size distribution (DMA-selected electrical mobility diameter 60 nm, Ag particles produced within CAIMAN [23]).

Figure 1 highlights the presence of multiple-charge particles (equivalent electrical mobility diameter of approximately 90 nm). However, in the remainder of this paper, only the DMA-selected particle diameter will be considered, the proportion of multiple-charge particles being below about 5 % of the total number and thus considered negligible.

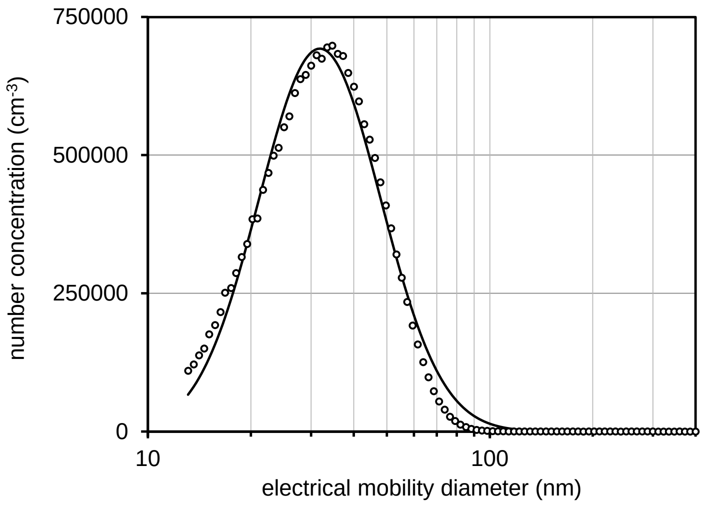

Figure 2. Example of polydisperse number size distribution (Al particles produced within the CAIMAN facility [23]).

2.2. Reference instruments

The reference particle number concentration ($C_{N,\mathrm{ref}}$) was provided by a Condensation Particle Counter (CPC; Grimm 5.401, d_{50} = 4.5 nm, $Q_{aerosol}$ = 1.5 L min^{-1}), while the reference number size distribution was determined by a Scanning Mobility Particle Sizer (SMPS; Grimm, composed of a Vienna Type Differential Mobility Analyzer — DMA — and a CPC 5.403, $Q_{aerosol}$ = 0.3 L min^{-1}, Q_{sheath} = 3 L min^{-1}). A lognormal model was fitted by a least squares method to obtain the modal diameter of the distribution (e.g., Figure 2), considered as the reference diameter (d_{ref}) in polydisperse mode. Both reference devices are "gold-standard" instruments and were calibrated prior to the measurement campaigns.

In monodisperse mode, the DMA-selected particle electrical mobility diameter was considered as the reference diameter (d_{ref}).

2.3. Instruments under study

2.3.1. Electrical mobility spectrometers.

Although not ideally suited to the monitoring of aerosols in workplaces due to their low time-resolution, lack of field-portability, complexity of use and high cost [24, 25], SMPS as well as FMPS were examined in this study. Despite their drawbacks in the field, these devices are research-grade instruments, which make it is possible to accurately measure aerosol parameters for laboratory studies [26]. Only a single specimen of each instrument was studied. The SMPS was from TSI (DMA 3081, CPC model 3787, $Q_{aerosol}$ = 0.6 L.min^{-1}, Q_{sheath} = 6 L.min^{-1}).

In addition, a new portable and battery-operated version of the SMPS, commercialized by TSI and named Nanoscan, allows airborne particle number size distribution to be measured in one minute over a size range of 10 to 420 nm. Three specimens of Nanoscan TSI were investigated in this work.

For all these devices, measured number size distributions were adjusted by means of a monomodal lognormal model; the modal diameter of the fitted distribution is considered in the remainder of this paper.

2.3.2. Diffusion chargers
Real-time portable and battery-operated devices based on particle diffusion charging and sequential electrical measurement were also investigated in this study. The DiSCmini (Matter Aerosol AG, Switzerland), developed by Fierz *et al.* [27], is a standalone real-time handheld instrument that provides the airborne nanoparticle number concentration (C_N, 10^3 – 10^6 cm^{-3}) and average diameter (d, 20 - 300 nm) with an accuracy of ± 30% according to the manufacturer [28, 29]. To avoid artifacts due to coarse particles, the DiSCmini is equipped with an inlet separator with a cutoff diameter of 700 nm. This device has previously been studied in laboratory conditions [30-33] as well as in field conditions [34-36]. In this study, ten specimens of DiSCmini were challenged by the different test aerosols.

The NanoTracer diffusion charger developed by Philips Aerasense [37] and licensed to Oxility (Eindhoven, Netherlands) has similar characteristics to the DiSCmini, and reports the average diameter and number concentration of airborne particles. The NanoTracer has been used in combination with GPS tracking, for example, to assess the contribution of different activities to personal exposure [38, 39]. One specimen of NanoTracer was investigated in this work.

2.4. Methods
Experiments consisted of measuring in parallel the aerosols produced during a 5- to 30-minute period when the test aerosol is stable and when a sufficient number of scans can be measured by means of (1) the reference instruments and (2) the instruments under study. Due to the large number of devices investigated, experiments were replicated to allow all instruments to be challenged by a sufficient number of aerosols.

The data treatment procedure was as follows:

- For each test aerosol, the average number concentration $\overline{C_N}$ and the corresponding standard deviation $\sigma(C_N)$ were calculated for all instruments.
- Data points presenting a coefficient of variation above 5 % were disregarded, i.e. when

$$\frac{\sigma(C_N)}{\overline{C_N}} > 5\ \%$$

- For each of the remaining data points, the following ratios were calculated:
  - the ratio R_C between the concentration measured by the instrument under study ($\overline{C_N}$) and the corresponding reference concentration ($\overline{C_{N,\mathrm{ref}}}$):

$$R_C = \frac{\overline{C_N}}{\overline{C_{N,ref}}}$$

  - the ratio R_d between the modal (or average) diameter provided by the instrument under study ($\bar{d}$) and the corresponding reference diameter (d_{ref}):

$$R_d = \frac{\bar{d}}{d_{ref}}$$

- This calculation was performed for all test aerosols, and the data were presented as boxplots. In these graphs, the box surrounding the median value corresponds to the 1st and 3rd quartiles, while the error bars represent the 95% confidence interval.

3. Results
The following subsections present the experimental results obtained for both the electrical mobility spectrometers and the diffusion chargers. The latter results, expressed as ratios, are displayed as boxplots, i.e. the closer to unity the ratio, the better the agreement between the instrument under study and the reference.

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3.1. Electrical mobility spectrometers

Figure 3 presents the experimental results obtained for electrical mobility spectrometers in terms of diameter ratio (R_d, top), and number concentration ratio (R_C, bottom), relative to the reference.

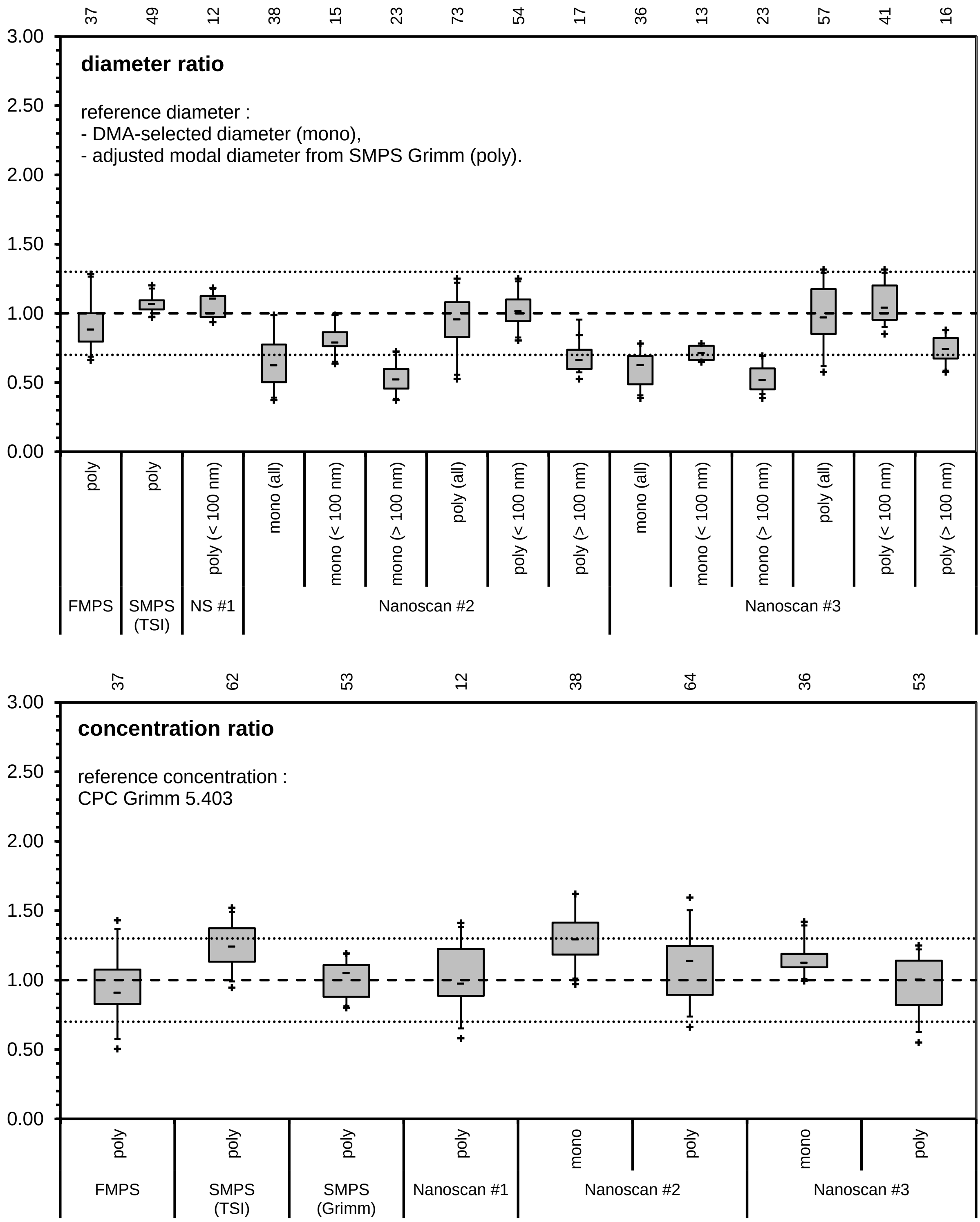

Figure 3. Boxplot of the diameter ratios (top) and number concentration ratios (bottom) found for the electrical mobility spectrometers (NS: Nanoscan).

The diameter ratios in Figure 3 show that the FMPS and SMPS are in close agreement with the reference particle diameter, within ± 30% in most cases. Nanoscans #2 and #3 underestimated particle diameter when challenged by aerosols composed of particles above 100 nm, by approximately -30% to -50%. On the contrary, all Nanoscans under investigation reported size distributions in agreement with the reference within ± 30% when measuring both mono- and polydisperse aerosols with (modal) diameters below 100 nm.

In terms of number concentration, all of the instruments investigated were in agreement with the reference concentrations, within ± 30 %, except the Nanoscan #2. It is important to remember that for all of these devices, the reported number concentration is derived from a calculation internal to the software that takes into account the electrical state of charge of the particles as well as the transfer function through the DMA. Based on physical assumptions, such inversion computations can lead to under- or overestimation of number concentrations. Larger discrepancies have previously been reported elsewhere, e.g. [40, 41].

3.2. Diffusion chargers

Figure 4 presents the experimental results obtained for various diffusion chargers in terms of diameter ratio (top), and number concentration ratio (bottom), relative to the reference. Because of their operating principles, the two ratios will be considered in parallel. Indeed, particle size and concentration are strongly dependent on each other due to the charging law, e.g. [27, 37].

3.2.1. DiSCmini

Ten specimens of DiSCmini were investigated in this study. According to Figure 4, they all behave similarly; the devices report particle sizes smaller than the reference, leading to an overestimation of the corresponding total number concentration.

More particularly, median diameter ratios of between 0.60 and 0.89 (respective relative discrepancies between -40% and -11%) were observed, the test aerosols being either mono or polydisperse. The number concentrations reported by the DiSCmini specimens were found to be somewhat higher than the reference, with the exception of model “DM CIOP 5”, whose range of median ratios of 1.17 to 2.44 is not in line with the manufacturer’s specifications of ± 30% (dotted lines).

3.2.2. Case of Nanotracer

Only one Nanotracer specimen was studied. Thus, the results reported here are less robust than those obtained for the DiSCmini. Nevertheless, Figure 4 suggests that this Nanotracer slightly overestimates particle diameter, by a factor of 15% on average. On the other hand, this results in an underestimation of particle number concentration, by about -30%. Investigations with multiple specimens of Nanotracer are required to better assess their behavior with respect to the reference instrument.

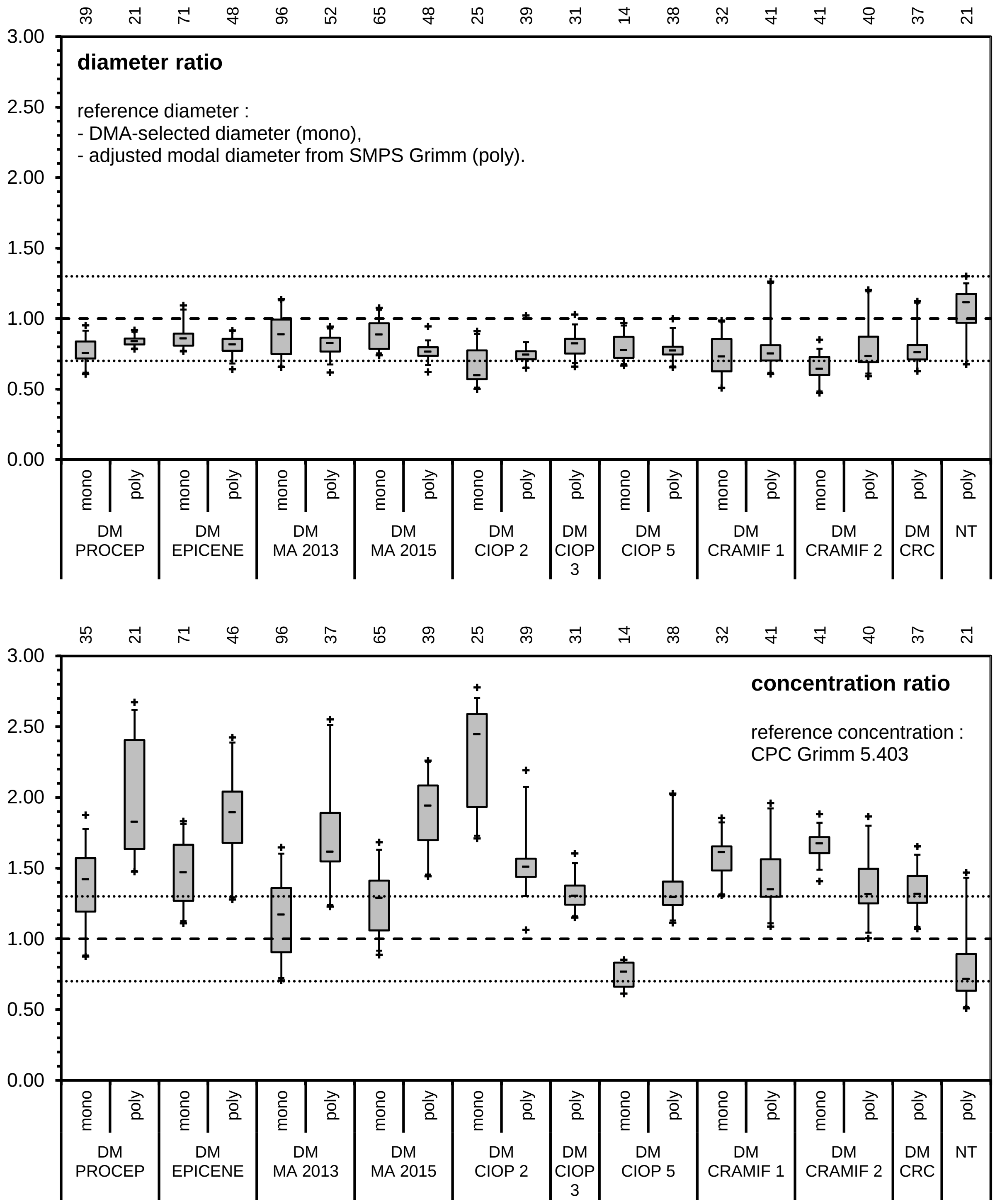

Figure 4. Boxplot of the diameter ratios (top) and concentration ratios (bottom) determined/measured by the diffusion chargers (DM: DiSCmini, NT: Nanotracer).

4. Conclusion

This study focused on the performances of real-time instruments devoted to the measurement of airborne particles. Gold-standard devices such as electrical mobility spectrometers (transportable and portable instruments) as well as personal portable diffusion chargers were investigated. All instruments were challenged by a set of monodisperse and polydisperse test aerosols covering a wide range of (modal) diameters and number concentrations. The values for these two parameters reported by these devices were compared to reference instruments, such as SMPS for the number size distribution and CPC for the total number concentration.

The experimental results obtained for the group of electrical mobility spectrometers highlight the good agreement between SMPS and FMPS and the reference. A slight tendency for the Nanoscan to underestimate particle size distribution when the particles were larger than around 100 nm was observed, and was probably due to the decrease in selectivity of the radial DMA used in the Nanoscan.

The data reported for the group of diffusion chargers demonstrate that all except the Nanotracer show a tendency to underestimate particle diameter. For the 10 DiSCminis studied, acceptable discrepancies of around -40% to -10% were observed. In the case of particle concentration, larger deviations were observed. However, in our opinion, this is probably not important when the relative concentrations provided by, for example, two DiSCmini operated in parallel are being used to conclude whether or not a given activity leads to a significant nanoparticle release. Nevertheless, this device is sensitive enough to be used as a nanoparticle monitor, e.g. in workplaces where nanomaterials are handled or produced, provided that the aerosol being measured is not composed only of particles larger than the upper limit of 300 nm.

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References
[1] SAVOLAINEN K., PYLKKÄNEN P., NORPPA H., FALCK G., LINDBERG H., TUOMI T., *et al.* - Nanotechnologies, engineered nanomaterials and occupational health and safety – A review. *Safety Sci.*, 2011, **48,** 957-963.
[2] SHEPARD M. N. & BRENNER S. - An occupational exposure assessment for engineered nanoparticles used in semiconductor fabrication. *Ann. Occup. Hyg.*, 2013, **58,** 251-265.
[3] GORDON S. C., BUTALA J. H., CARTER J. M., ELDER A., GORDON T., GRAY G., *et al.* - Workshop report: Strategies for setting occupational exposure limits for engineered nanomaterials. *Regul. Toxicol. Pharm.*, 2014, **68,** 305-311.
[4] O'SHAUGHNESSY P. T. - Occupational health risk to nanoparticulate exposure. *Environ. Sci.: Processes Impacts*, 2013, **15,** 49-62.
[5] WANG J., ASBACH C., FISSAN H., HÜLSER T., KUHLBUSCH T. A. J., THOMPSON D., *et al.* - How can nanobiotechnology oversight science and industry: examples from environmental, health, and safety studies of nanoparticles (nano-EHS). *J. Nanopart. Res.*, 2011, **13,** 1373-1387.
[6] BROUWER D., VAN DUUREN-STUURMAN B., BERGES M., JANKOWSKA E., BARD D., & MARK D. - From workplace air measurement results towards estimates of exposure? Development of a strategy to assess exposure to manufactured nano-objects. *J. Nanopart. Res.*, 2009, **11,** 1867-1881.
[7] BROUWER D. - Exposure to manufactured nanoparticles in different workplaces. *Toxicology*, 2010, **269,** 120-127.
[8] KUHLBUSCH T., ASBACH C., FISSAN H., GÖHLER D., & STINTZ M. - Nanoparticle exposure at nanotechnology workplaces: A review. *Part. Fiber Toxicol.*, 2011, **8,** 22.
[9] RAMACHANDRAN G., OSTRAAT M., EVANS D. E., METHNER M. M., O'SHAUGHNESSY P., D'ARCY J., *et al.* - A strategy for assessing workplace exposures to nanomaterials. *Journal of Occupational and Environmental Hygiene*, 2011, **8,** 673-685.
[10] WITSCHGER O., LEBIHAN O., REYNIER M., DURAND C., MARCHETTO A., ZIMMERMANN E., *et al.* - Préconisations en matière de caractérisation des potentiels

d'émission et d'exposition professionnelle aux aérosols lors d'opérations mettant en oeuvre des nanomatériaux. *Hygiène et Sécurité au Travail*, 2012, **226,** 41-55.

[11] METHNER M., HODSON L., & GERACI C. - Nanoparticle emission assessment technique (NEAT) for the identification and measurement of potential inhalation exposure to engineered nanomaterials – part A. *Journal of Occupational and Environmental Hygiene*, 2010, **7,** 127-132.

[12] OSTRAAT M. L., THORNBURG J. W., & MALLOY Q. G. J. - Measurement strategies of airborne nanomaterials. *Environ. Eng. Sci.*, 2013, **30,** 126-132.

[13] METHNER M., HODSON L., DAMES A., & GERACI C. - Nanoparticle emission assessment technique (NEAT) for the identification and measurement of potential inhalation exposure to engineered nanomaterials – part B: results from 12 field studies. *Journal of Occupational and Environmental Hygiene*, 2010, **7,** 163-176.

[14] METHNER M., BEAUCHAM C., CRAWFORD C., HODSON L., & GERACI C. - Field application of the Nanoparticle Emission Assessment Technique (NEAT): task-based air monitoring during the processing of Engineered Nanomaterials (ENM) at four facilities. *Journal of Occupational and Environmental Hygiene*, 2012, **9,** 543-555.

[15] RAYNOR P. C., INGRAHAM CEBULA J., SPANGENBERGER J. S., OLSON B. A., DASCH J. M., & D'ARCY J. B. - Assessing potential nanoparticle release during nanocomposite shredding using direct-reading instruments. *Journal of Occupational and Environmental Hygiene*, 2012, **9,** 1-13.

[16] KOIVISTO A. J., LYYRÄNEN J., AUVINEN A., VANHALA E., HÄMERI K., TUOMI T., *et al.* - Industrial worker exposure to airborne particles during the packing of pigment and nanoscale titanium dioxide. *Inhal. Toxicol.*, 2012, **24,** 839-849.

[17] PETERS T. M., HEITBRINK W. A., EVANS D. E., SLAVIN T. J., & MAYNARD A. D. - The mapping of fine and ultrafine particle concentrations in an engine machining and assembly facility. *Ann. Occup. Hyg.*, 2006, **50,** 249-257.

[18] HEITBRINK W. A., LO L.-M., & DUNN K. H. - Exposure Controls for Nanomaterials at Three Manufacturing Sites. *J. Occup. Environ. Health*, 2014**,** in press, DOI: 10.1080/15459624.15452014.15930559.

[19] BUONANNO G., JAYARATNE R. E., MORAWSKA L., & STABILE L. - Metrological Performances of a Diffusion Charger Particle Counter for Personal Monitoring. *Aerosol Air Qual. Res.*, 2014, **14,** 156-167.

[20] VOSBURGH D. J. H., KU B. K., & PETERS T. M. - Evaluation of a Diffusion Charger for measuring aerosols in a workplace. *Ann. Occup. Hyg.*, 2014, **58,** 424-436.

[21] CEN - prEN 17058, Workplace exposure — Assessment of inhalation exposure to nano-objects and their agglomerates and aggregates, 2016.

[22] CEN - prEN 16966, Workplace exposure – Metrics to be used for the measurements of exposure to inhaled nanoparticles (nano-objects and nanostructured materials) such as mass concentration, number concentration and surface area concentration, 2016.

[23] JACOBY J., BAU S., & WITSCHGER O. - CAIMAN: a versatile facility to produce aerosols of nanoparticles. *Journal of Physics: Conference Series*, 2011, **304,** 012014.

[24] LESKINEN J., JOUTSENSAARI J., LYYRÄNEN J., KOIVISTO J., RUUSUNEN J., JÄRVELÄ M., *et al.* - Comparison of nanoparticle measurement instruments for occupational health applications. *J. Nanopart. Res.*, 2012, **14,** 718-733.

[25] STABILE L., CAUDA E., MARINI S., & BUONANNO G. - Metrological assessment of a portable analyzer for monitoring the particle size distribution of ultrafine particles. *Ann. Occup. Hyg.*, 2014, **58,** 860-876.

[26] WITSCHGER O. - Monitoring nanoaerosols and occupational exposure, in *Nanoethics and nanotoxicology*, eds. Houdy, P., Lahmani, M., & Marano, F. (Springer Verlag, Berlin Heidelberg), pp. 163-199.

[27] FIERZ M., HOULE C., STEIGMEIER P., & BURTSCHER H. - Design, calibration, and field performance of a Miniature Diffusion Size Classifier. *Aerosol Science and Technology*, 2011, **45,** 1-10.

[28] MATTER AEROSOL - *DiSCmini instruction manual Rev. 1.10*, 2012.

[29] TESTO - http://testo-partikel.de/files/DiSCmini_EN_compressed.pdf (2016-11-02)

[30] BAU S., ZIMMERMANN B., PAYET R., & WITSCHGER O. - Laboratory study of the performance of the miniature Diffusion Size Classifier (DiSCmini) for various aerosols in the 15-400 nm range. *Environmental Science: Processes and Impacts*, 2015, **17,** 261-269.

[31] ASBACH C., KAMINSKI H., VON BARANY D., KUHLBUSCH T. A. J., MONZ C., DZIUROWITZ N., *et al.* - Comparability of portable nanoparticle exposure monitors. *Ann. Occup. Hyg.*, 2012, **56,** 606-621.

[32] MILLS J. B. - Evaluation of the DiSCmini personal aerosol monitor for submicrometer sodium chloride and metal aerosols, 2013, University of Iowa.

[33] MILLS J. B., PARK J. H., & PETERS T. M. - Comparison of the DiSCmini aerosol monitor to a handheld condensation particle counter and a scanning mobility particle sizer for submicrometer sodium chloride and metal aerosols. *Journal of Occupational and Environmental Hygiene*, 2013, **10,** 250-258.

[34] MEIER R., CLARK K., & RIEDIKER M. - Comparative testing of a Miniature Diffusion Size Classifier to assess airborne ultrafine particles under field conditions. *Aerosol Science and Technology*, 2013, **47,** 22-28.

[35] KIM B., KIM H., & YU I. J. - Assessment of nanoparticle exposure in nanosilica handling process: including characteristics of nanoparticles leaking from a vacuum cleaner. *Ind. Health*, 2014, **52,** 152-162.

[36] OH S., KIM B., & KIM H. - Comparison of nanoparticle exposures between fumed and sol-gel nano-silica manufacturing facilities. *Ind. Health*, 2014, **52,** 190-198.

[37] MARRA J., VOETZ M., & KIESLING H. J. - Monitor for detecting and assessing exposure to airborne nanoparticles. *J. Nanopart. Res.*, 2010, **12,** 21-37.

[38] BUONANNO G., STABILE L., & MORAWSKA L. - Personal exposure to ultrafine particles: the influence of time-activity patterns. *Science of the Total Environment*, 2014, **468-469,** 903-907.

[39] BEKÖ G., KJELDSEN B. U., OLSEN Y., SCHIPPERIJN J., WIERZBICKA A., KAROTTKI D. G., *et al.* - Contribution of various microenvironments to the daily personal exposure to ultrafine particles: Personal monitoring coupled with GPS tracking. *Atmos. Environ.*, 2015, **110,** 122-129.

[40] FRANK B. P., SALTIEL S., HOGREFE O., GRYGAS J., & LALA G. G. - Determination of mean particle size using the electrical aerosol detector and the condensation particle counter: comparison with the scanning mobility particle sizer. *Journal of Aerosol Science*, 2008, **39,** 19-29.

[41] LIU P. S. K. & DESHLER T. - Causes of concentration differences between a scanning mobility particle sizer and a condensation particle counter. *Aerosol Science and Technology*, 2003, **37,** 916-923.