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Original Article

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Performance Comparison of Field Portable Instruments to the Scanning Mobility Particle Sizer Using Monodispersed and Polydispersed Sodium Chloride Aerosols

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Abstract

This study compared the performance of the following field portable aerosol instrument sets to performance of the reference Scanning Mobility Particle Sizer (SMPS): the handheld CPC-3007, the portable aerosol mobility spectrometer (PAMS), the NanoScan scanning mobility particle sizer (NanoScan SMPS) combined with an optical particle sizer (OPS). Tests were conducted with monodispersed and polydispersed aerosols. Monodispersed aerosols were controlled at the approximate concentration of 1×10^5 particles cm^{-3} and four monodispersed particle sizes of 30, 60, 100, and 300 nm were selected and classified for the monodispersed aerosol test, while three different steady-state concentration levels (low, medium, and high: ~8×10^3, 5×10^4, and 1×10^5 particles cm^{-3}, respectively) were selected for the polydispersed aerosol test. For all four monodispersed aerosol sizes, particle concentrations measured with the NanoScan SMPS were within 13% of those measured with the reference SMPS. Particle concentrations measured with the PAMS were within 25% of those measured with the reference SMPS. Concentrations measured with the handheld condensation particle counter were within 30% of those measured with the reference SMPS. For the polydispersed aerosols, the particle sizes and concentrations measured with the NanoScan-OPS compared most favorably with those measured with the reference SMPS for three different concentration levels of low, medium, and high (concentration deviations ≤10% for all three concentration levels; deviations of particle size ≤4%). Although the particle-size comparability between the PAMS and the reference SMPS was quite reasonable with the deviations within 10%, the polydispersed particle concentrations measured with the PAMS were within 36% of those measured with the reference SMPS. The results of this evaluation will be useful for selecting a suitable portable device for our next workplace study phase of respiratory protection assessment. This study also provided the advantages and limitations

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of each individual portable instrument and therefore results from this study can be used by industrial hygienists and safety professionals, with appropriate caution, when selecting a suitable portable instrument for aerosol particle measurement in nanotechnology workplaces.

Keywords: handheld CPC; monodispersed and polydispersed aerosols; NanoScan SMPS; OPS; portable aerosol instrument; PAMS

Introduction

Engineered nanomaterials are rapidly becoming a part of the daily life in the form of electron field emitters, conductive devices (Endo *et al.*, 2008; Wang *et al.*, 2011), chemical sensors and catalysts (McKinney *et al.*, 2009), and medical devices (Chakravarty *et al.*, 2008). Despite obvious benefits of the power of nanomaterials, there are questions about the toxicity and environmental impact. Nanomaterial particles may be inhaled, ingested, or absorbed through skin (Baroli *et al.*, 2007). Inhalation of nanoparticles is believed to be the primary route of exposure and is of the greatest concern (Birch *et al.*, 2011).

One great interest to the health protection community is to develop reliable measurement methods for the evaluation and selection of respiratory protection and control technology for use in nanotechnology workplaces. Several direct-reading instruments are available for workplace aerosol monitoring, which include handheld condensation particle counters (CPCs), nanoTracer, Aerotrak, and optical particle counters (OPCs) (Asbach *et al.*, 2012). These instruments are suitable for routine use for measurement of the particle counts and providing evidence of the presence of nanomaterials in air. To obtain the particle count, mass-based concentration, and size distribution of an aerosol in a single measurement, larger mobility spectrometers, such as the scanning mobility particle spectrometer (SMPS) and aerodynamic particle sizer (APS), are traditionally used. However, the SMPS and APS, which are intended for benchtop research laboratory use, are bulky and expensive instruments, making them impractical for routine field use. Recent advances in aerosol instrument technology have made it possible to produce smaller instruments ('backpack'-sized instruments), such as the NanoScan scanning mobility particle sizer (NanoScan SMPS), optical particle sizers (OPSs), and portable aerosol mobility spectrometers (PAMSs). These portable instruments can be used to determine a detailed picture of workplace particles, including the particle counts and size distributions.

Results concerning comparisons of field portable instruments have previously been published (Asbach *et al.*, 2012; Liu *et al.*, 2014). The study of Asbach *et al.* (2012) was targeted to an intensive comparison between portable instruments, including nanoTracer, nanoCheck, Aerotrak 9000, and handheld CPCs, using only polydispersed aerosols under defined laboratory conditions while the study of Liu *et al.* (2014) focused only on the variability and accuracy of the same portable instrument models (between two handheld CPCs or two OPCs). Different portable aerosol instruments reacted quite differently to the different aerosol concentration levels and particle sizes (Asbach *et al.*, 2012), so the accurate method for evaluating and comparing among portable aerosol instruments is to: (i) use the same particle size and the same particle concentration levels (a monodispersed aerosol particle method) and (ii) use the same particle distribution range and the same particle concentration level (a polydispersed aerosol particle method). Although the study of Mills *et al.* (2013) applied the monodispersed and polydispersed aerosol particles for comparing the DiSCmini aerosol monitor to the reference handheld CPC and SMPS, we have been unable to identify any literature reports relating to the use of the monodispersed and polydispersed aerosol particle methods for evaluating and comparing among the PAMS, OPS, and NanoScan SMPS.

Thus, the aims of this study were to (i) evaluate the performance of the portable aerosol instruments, including the handheld CPC, PAMS, OPS, and NanoScan SMPS, regarding their utility for evaluating and selecting respiratory protection in the workplace and (ii) to compare the measurements made with the handheld CPC, PAMS, OPS, and NanoScan SMPS with those measured with the reference SMPS. It should be noted that the performance comparison of the CPC, PAMS, and NanoScan SMPS to the SMPS was evaluated in terms of particle concentration using monodispersed sodium chloride (NaCl) aerosols, while the performance comparison of the PAMS and NanoScan-OPS combined to the SMPS was evaluated in terms of particle concentration and particle size distributions using polydispersed NaCl aerosols. The results of this evaluation will be useful for selecting a suitable portable device for our next workplace study (field study) phase of respiratory protection assessment and also of use to industrial hygienists and safety professionals who are selecting sampling methods for use in the workplace.

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Materials and methods

Evaluation of portable instruments against monodispersed NaCl aerosols

Monodispersed aerosol test method

In order to produce dry aerosols, stable particle concentration levels, and the same particle size, a monodispersed aerosol testing system was designed in three stages: (i) generating polydispersed aerosols, (ii) producing monodispersed aerosols, and (iii) measuring monodispersed aerosols (Fig. 1). In the generating polydispersed aerosol stage, a 0.2% NaCl solution in distilled water was aerosolized using the six-jet atomizer (Model 9306, TSI, Shoreview, MN, USA) and the output aerosol was dried with 30% dilution air in a self-contained dilution system within the atomizer and then continued to be dried with a diffusion dryer. The aerosol stream passed through a neutralizer with a Kr-85 charging source (Model 3054, TSI) before entering into the 9000-L testing chamber (height, width, and depth of 2.5 × 2.5 × 1.5 m, respectively; Model 222-6, Dynatech, Albuquerque, NM, USA). The aerosols in the chamber were mixed using four internal fans positioned on the top of the four inner corners of the chamber (Fig. 1). Throughout the experiment, an ultrafine CPC monitored the total particle concentration at a flowrate of 0.3 liter per minute (LPM) (Fig. 1). During particle generation and sampling, NaCl aerosol particles were continuously dispersed into the chamber, while the exhaust port was in the open position to remove excess air and maintain neutral pressure. Polydispersed aerosols in the 9000-L chamber were controlled and maintained at the concentration level of ~1×10^5 particles cm^{-3}. In the producing monodispersed aerosol stage, polydispersed aerosols were pumped out from the 9000-L chamber using an electric pump and the polydispersed aerosol stream entered into an electrostatic classifier (size classifier, Model 3080, TSI) equipped with a differential mobility analyzer (DMA, Model 3081, TSI) at the flow rate of 3 LPM to produce monodispersed test aerosols. The DMA is an integral part of the SMPS system that classifies particles based on electrical mobility. The selected monodispersed aerosol exiting the DMA were then introduced into a 5-L chamber (Fig. 1). Four monodispersed aerosol sizes of 30, 60, 100, and 300 nm were selected and classified for this study. These four monodispersed particle

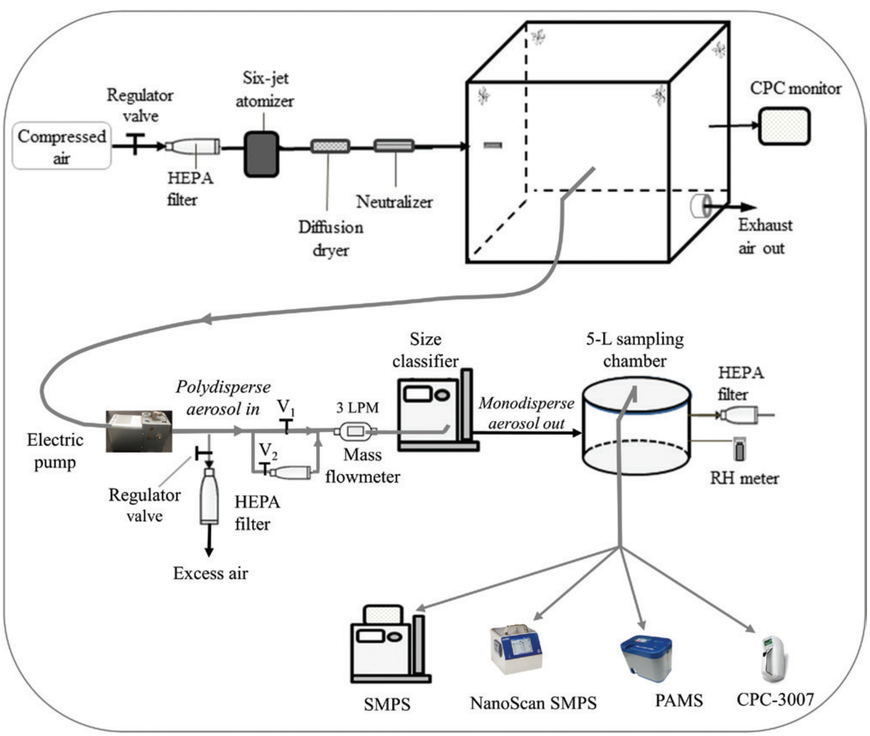

Figure 1. Schematic diagram of monodispersed aerosol testing system. During a test experiment, the zero-filter assembly was off [regulator valve (V1): open; valve (V2): close]; the zero-filter assembly was on [valve (V1): close; valve (V2): open] for particle cleaning after completing tests for each monodispersed aerosol size.

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sizes were selected because a small amount of larger monodispersed particle sizes (particles >300 nm) was generated from the NaCl suspension solution. During particle sampling, each monodispersed aerosol particle size was continuously produced into the 5-L chamber, while the chamber conditions were tracked by a humidity/temperature sensor (Model RHXL3SD, Omega Engineering, Stamford, CT, USA) (Fig. 1). In the measuring monodispersed aerosol stage, three portable aerosol instruments: Handheld CPC (Model 3007, TSI), PAMS (Model 3310 with an external charger; Kanomax, Shimizu Suita City, Osaka, Japan), and NanoScan SMPS (Model 3910, TSI) were used to measure monodispersed particle concentrations. The aerosol inlets were set at 0.70 LPM for the handheld CPC and the PAMS and 0.75 LPM for the NanoScan SMPS. A SMPS system which consists of an electrostatic classifier (Model 3080, TSI), a DMA (Model 3081, TSI), and a CPC (Model 3772, TSI) was used as a reference SMPS (aerosol flow rate at 0.3 LPM and aerosol density of 1.2 g cm^{-3}) to measure monodispersed particle concentrations. To overcome the particle loss issue among different instruments in this study, the same sampling tubing type and tubing diameter were used. The lengths of the sampling tubing used for each test instrument were calculated based on the ratio of their sample-inlet airflow rates. For each monodispersed aerosol size, all portable instruments and the reference SMPS were run three replicate tests (n = 3) and a 2-min sampling time for each test.

Comparison of the monodispersed aerosol data

The particle concentrations measured with each portable instrument and the reference SMPS for each monodispersed aerosol size of 30, 60, 100, and 300 nm were compared two ways: particle concentrations between each portable instrument and the reference SMPS using a scatter plot were compared as well as a comparing the percentage difference or the concentration ratio (R_m) between each portable instrument and the reference SMPS. The percentage difference was calculated as: [(|portable device concentration − reference SMPS concentration|/reference SMPS concentration) × 100]. The R_m was defined as follows:

$$R_{m,\ CPC} = \frac{C_{CPC}}{C_{SMPS}},\ R_{m,\ NanoScan} = \frac{C_{NanoScan}}{C_{SMPS}},\ \text{and}\ R_{m,\ PAMS} = \frac{C_{PAMS}}{C_{SMPS}} \quad (1)$$

where C_{CPC}, C_{SMPS}, $C_{NanoScan}$, and C_{PAMS} are the total number concentration measured with the handheld CPC, reference SMPS, NanoScan SMPS, and the PAMS, respectively.

Evaluation of portable instruments against polydispersed NaCl aerosols

Polydispersed aerosol test method

Polydispersed aerosols were generated using the same procedure as described in the 'monodispersed aerosol test method' section (the first stage); however, polydispersed aerosols were measured directly from the 9000-L chamber (Fig. 2). Polydispersed aerosols were controlled

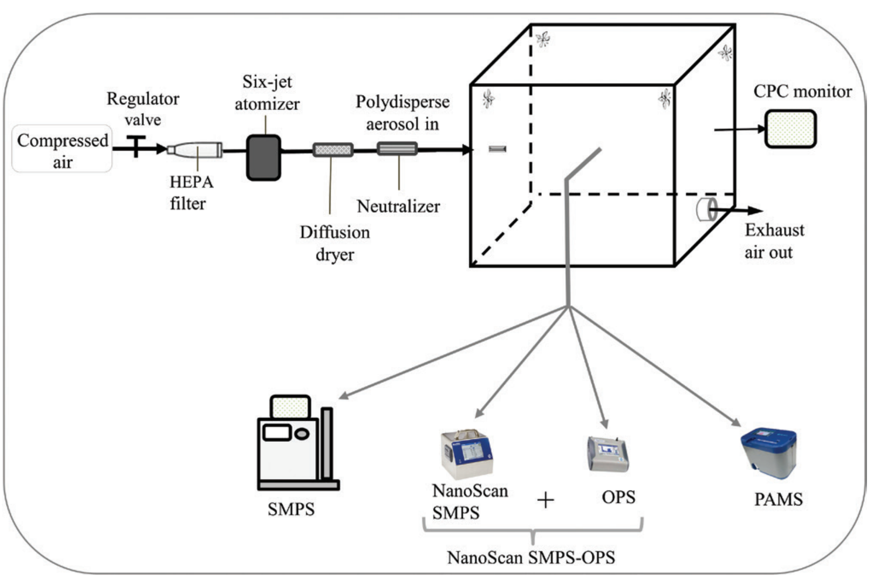

Figure 2. Schematic diagram of polydispersed aerosol testing system.

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in three different steady-state concentration levels: low (~8 × 10^3 particles cm^{-3}), medium (~5 × 10^4 particles cm^{-3}), and high (~1 × 10^5 particles cm^{-3}).

Three portable aerosol instruments: PAMS, NanoScan SMPS, and OPS were used to measure polydispersed aerosol particles (Fig. 2). A SMPS was used as a reference instrument to measure polydispersed aerosol particles. Unlike the handheld CPC which was able to measure only particle concentrations, PAMS, NanoScan SMPS, and OPS were used to measure both particle concentrations and size distributions. In this polydispersed aerosol test experiment, the aerosol inlet of 0.7 LPM and the wide range mode with a particle distribution range of 14–862 nm (wide range mode) were set for the PAMS. The OPS, NanoScan SMPS, and the reference SMPS are able to measure specific size ranges. NanoScan SMPS has a particle detection range of 10–420 nm, OPS has a detection range of 300–10 000 nm, and SMPS has a detection range of 10–1000 nm. In order to obtain the best accuracy for comparing among portable aerosol instruments and the reference SMPS, all of these instruments were set to the same particle size distribution of the PAMS (from 14 to 862 nm) and operated simultaneously. For the reference SMPS, a measurement of the particle distribution range of 14–862 nm was performed by setting an aerosol sample airflow mode. For the NanoScan SMPS and the OPS, the real-time particle size distributions from 14 to 862 nm was performed in two steps: (i) operating each instrument independently and (ii) pairing the NanoScan SMPS with the OPS for measuring real-time particle size distributions from 14 to 862 nm. The aerosol inlet of 0.75 LPM and the size range of 14–420 nm were set for the NanoScan SMPS while the aerosol inlet of 1.0 LPM and the size range of 300–862 nm were set for the OPS. Combining each data set of the NanoScan SMPS and OPS into a single size distribution (14–862 nm) was performed using Aerosol Instrument Manager (AIM) software (Version 9.0, TSI) by calculating the ratio of the overlapping size range between 300 and 420 nm. In this article, each test NanoScan SMPS and OPS size distribution data were combined and designated as the 'NanoScan-OPS' set. All NanoScan-OPS sets were reported in the mobility equivalent diameter as a function of the count-based concentration. For each polydispersed aerosol concentration level, all portable instruments and the reference SMPS were run three replicate tests and a 2-min sampling time for each test.

Comparison of the polydispersed aerosol data

Particle concentrations and particle distribution data measured with the PAMS and NanoScan-OPS for each polydispersed aerosol concentration level were compared with those measured by the reference SMPS in three ways: directly comparing particle concentrations and size distributions based on instrumental spectra, comparing polydispersed aerosol concentration ratio (R_p) or the percentage difference based on the summation of particle concentration across the size range of 14–862 nm, and comparing polydispersed aerosol size ratio (R_{ps}). Directly comparing particle concentrations and size distributions, which express the number-based concentration (dN/dlog Dp; #/cm^3) as a function of particle diameter, was obtained directly from the portable aerosol instruments and the reference SMPS. The R_p was defined as follows:

$$R_{\text{p, NanoScan-OPS}} = \frac{C_{\text{NanoScan-OPS}}}{C_{\text{SMPS}}}, \text{ and } R_{\text{p, PAMS}} = \frac{C_{\text{PAMS}}}{C_{\text{SMPS}}} \quad (2)$$

where $C_{\text{NanoScan-OPS}}$, C_{SMPS}, and C_{PAMS} are the summation concentrations measured with the NanoScan-OPS combined, reference SMPS, and the PAMS, respectively.

The ratio of the particle size was calculated as:

$$R_{\text{ps, NanoScan-OPS}} = \frac{d_{\text{NanoScan-OPS}}}{d_{\text{SMPS}}}, \text{ and } R_{\text{ps, PAMS}} = \frac{d_{\text{PAMS}}}{d_{\text{SMPS}}} \quad (3)$$

where $d_{\text{NanoScan-OPS}}$, d_{SMPS}, and d_{PAMS} are the average geometric mean diameter (GMD) measured with the NanoScan-OPS combined, reference SMPS, and the PAMS, respectively.

Data analysis

All averages, standard deviation and the coefficient of variation (CV) values, concentration ratios, and particle size ratios were analyzed using Microsoft® Excel 2010 software (Microsoft Corporation, Redmond, WA, USA). A linear regression between each portable instrument data and the reference SMPS data was also performed using Microsoft® Excel 2010 software. The coefficient of determination (R^2) was used to describe the correlation of measured levels between each portable instrument and the reference SMPS. Paired *t*-tests with two-tailed distribution were also performed to analyze the differences in particle concentrations measured with the portable instruments and the reference SMPS against polydispersed NaCl aerosols also using Microsoft® Excel 2010. *P*-values of <0.05 were considered significant.

Results

Evaluation of portable instruments against monodispersed NaCl aerosols

A scatter plot of the total number concentrations for the four monodispersed NaCl aerosol sizes of 30, 60, 100, and 300 nm measured with the handheld CPC, PAMS,

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NanoScan SMPS, and the reference SMPS is shown in Fig. 3. The dash diagonal line in Fig. 3 is a unity line in which all ideal data points of the 1:1 correlation would fall. A summary of average total number concentrations and ratios of monodispersed particle concentrations measured with the handheld CPC, PAMS, NanoScan SMPS, and the reference SMPS are listed in Table 1. In general, the monodispersed particle concentrations measured with the NanoScan SMPS compared most favorably with those measured with the reference SMPS, followed by the PAMS, and the handheld CPC. As shown in Table 1 and Fig. 3, number concentrations measured with the NanoScan SMPS were near unity values for all four monodispersed aerosol sizes ($R_{m, \text{NanoScan}}$: 0.87–1.05) and were within 13% of those measured with the reference SMPS. A regression analysis for the monodispersed aerosols also shows that there was a highly linear relationship among the number concentrations measured by the NanoScan SMPS and the reference SMPS with the coefficient $R^2 > 0.99$ and a slope of 0.98. For the PAMS, monodispersed particle concentrations were within 25% of those measured with the reference SMPS for all four monodispersed aerosol sizes (Table 1). The PAMS concentrations were much higher than unity values for small monodispersed particle sizes of 30 and 60 nm aerosols ($R_{m, \text{PAMS}}$: 1.25 and 1.22, respectively; Table 1; Fig. 3); however, the PAMS concentrations were below the unity values for larger monodispersed particle sizes of 100 and 300 nm aerosols ($R_{m, \text{PAMS}}$: 0.82 and 0.85, respectively; Table 1; Fig. 3). In addition, a regression analysis shows that there was a poor linear relationship among the number concentrations measured by the PAMS and the reference SMPS ($R^2 = 0.91$). For the handheld CPC, monodispersed particle concentrations were within 30% of those measured with the reference SMPS ($R_{m, \text{CPC}}$: 0.70–0.84; Table 1). Concentration ratios for the handheld CPC for all four monodispersed aerosol sizes were below the unity values (Fig. 3). With concentration ratios for all four monodispersed aerosol sizes being consistently below the unity values, it yielded a highly linear relationship among the number concentrations measured by the CPC and the reference SMPS ($R^2 = 0.98$); however, the handheld CPC had poor agreement with the reference SMPS with a slope of 0.70.

Evaluation of portable instruments against polydispersed NaCl aerosols

Polydispersed NaCl size distributions, which express the number-based concentration as a function of particle diameter, measured by the PAMS, NanoScan-OPS, and the reference SMPS at three different concentration levels: low (~8×10^3 particles cm^{-3}), medium (~5×10^4 particles cm^{-3}),

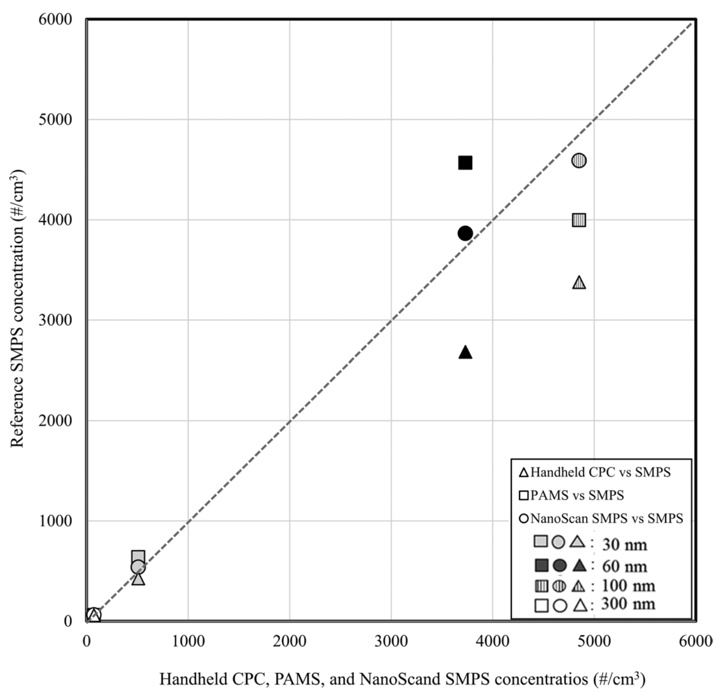

Figure 3. Total number concentration measured by the handheld CPC, PAMS, and NanoScan SMPS compared with that measured by the reference SMPS for monodispersed NaCl aerosols.

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and high (~1 × 10^5 particles cm^{-3}) are shown in Fig. 4. The paired *t*-tests ran for different number-based concentrations measured by the NanoScan-OPS and the reference SMPS as a function of particle diameter in each concentration level revealed all *P*-values ≥ 0.25. This indicates that there were not significant differences between the number-based concentrations obtained from the NanoScan-OPS and the reference SMPS in all three concentration levels tested. For the PAMS, the number-based concentrations were significantly different when compared with those measured with the reference SMPS in low and medium concentration levels tested (all *P*-values < 0.05), except for the high concentration level (*P*-value > 0.05).

The summation of polydispersed particle concentration across the size range of 14–862 nm and its concentration ratios measured with the NanoScan-OPS, PAMS, and the reference SMPS are listed in Table 2. The results in Table 2 and Fig. 5 show that the particle number concentrations measured with the NanoScan-OPS compared most favorably with those measured with the reference SMPS. The concentrations measured with the NanoScan-OPS were near unity values for all three polydispersed aerosol concentration levels ($R_{p,\ \mathrm{NanoScan\text{-}OPS}}$: 0.90–1.03) and were within 10% of those measured with the reference SMPS (Table 2). A regression analysis for the total polydispersed particle concentrations across the size range of 14–862 nm also shows that the NanoScan-OPS had a good agreement with the reference SMPS (R^2 > 0.99; slope = 0.95). For the PAMS, number concentrations were within 36% of those measured with the reference SMPS ($R_{p,\ \mathrm{PAMS}}$: 0.64–1.13; Table 2). Although number concentrations measured with the PAMS were within 13% of those measured with the reference SMPS for the high concentration level of ~1 × 10^5 particles cm^{-3}, number concentrations were much lower than unity values for the low and medium concentration levels of ~8 × 10^3 and 5 × 10^4 particles cm^{-3}, respectively ($R_{p,\ \mathrm{PAMS}}$: 0.64 and 0.80; Table 2).

Table 1. Average total number concentrations and ratios of monodispersed NaCl particles measured with the handheld CPC, PAMS, NanoScan SMPS, and the reference SMPS.

Particle size	SMPS (C_{SMPS}[a])	Handheld CPC		PAMS		NanoScan SMPS	
		C_{CPC}[a]	$R_{m,CPC}$[b]	C_{PAMS}[a]	$R_{m,PAMS}$[b]	$C_{NanoScan}$[a]	$R_{m,NanoScan}$[b]
30	510 ± 0.04	426 ± 0.08	0.84	638 ± 0.08	1.25	538 ± 0.07	1.05
60	3732 ± 0.04	2682 ± 0.04	0.72	4568 ± 0.04	1.22	3863 ± 0.05	1.04
100	4852 ± 0.03	3378 ± 0.08	0.70	3996 ± 0.04	0.82	4590 ± 0.04	0.95
300	72 ± 0.09	60 ± 0.04	0.83	61 ± 0.11	0.85	63 ± 0.04	0.87

[a]Mean total number concentration ± coefficient of variation (CV; *n* = 3 replicate tests).
[b]Monodispersed aerosol concentration ratios (R_m) of the portable device concentration (C_{CPC}, C_{PAMS}, or $C_{NanoScan}$) and reference SMPS concentration (C_{SMPS}).

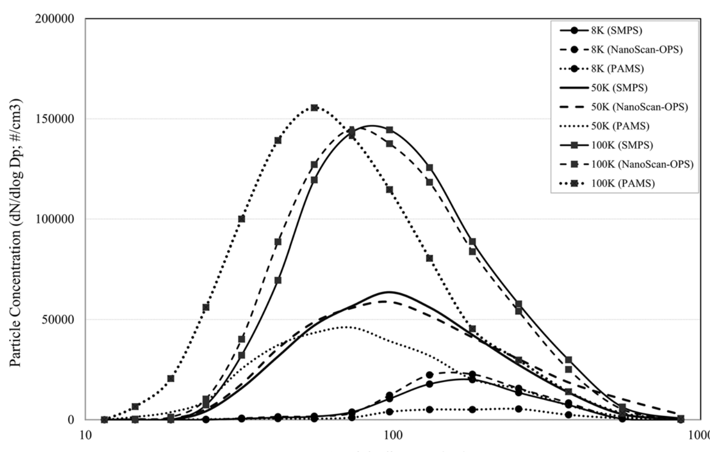

Figure 4. Size distributions of polydispersed NaCl aerosols measured by the PAMS, NanoScan SMPS-OPS combined, and the reference SMPS at three different concentration levels: low (~8 × 10^3 particles cm^{-3} or 8 K), medium (~5 × 10^4 particles cm^{-3}), and high (~1 × 10^5 particles cm^{-3}).

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Table 2. A summary of the summation of polydispersed particle concentration and its ratios across the size range of 14–862 nm measured with the NanoScan-OPS combined, PAMS, and the reference SMPS.

Concentration range[a]	SMPS (C_{SMPS}[b])	NanoScan-OPS combined		PAMS	
		$C_{Nano\text{-}OPS}$[b]	$R_{p,NanoScan\text{-}OPS}$[c]	C_{PAMS}[b]	$R_{p,PAMS}$[c]
L	8224 ± 0.07	8510 ± 0.07	1.03	5281 ± 0.26	0.64
M	50 128 ± 0.18	45 364 ± 0.11	0.90	40 120 ± 0.10	0.80
H	103 438 ± 0.12	98 664 ± 0.10	0.95	117 305 ± 0.09	1.13

[a]Concentration levels: low (L, ~8 × 10^3 particles/cm^3), medium (M, ~5 × 10^4 particles/cm^3), and high (H, ~1 × 10^5 particles/cm^3).
[b]Mean total number concentration ± CV (n = 3 replicate tests).
[c]polydispersed aerosol concentration ratios (R_p) of the portable device concentration ($C_{Nano\text{-}OPS}$ or C_{PAMS}) and reference SMPS concentration (C_{SMPS}).

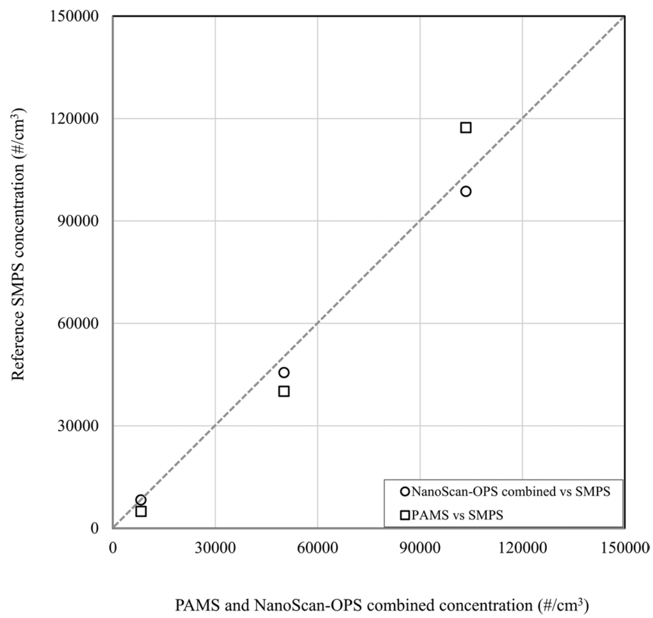

Figure 5. Total number concentration measured by the PAMS and the NanoScan-OPS combined compared with that measured by the reference SMPS for polydispersed aerosols.

A summary of the polydispersed aerosol size measurements, size ratios (R_{ps}), GMDs, and geometric standard deviations (GSDs) in the range of 14–862 nm is listed in Table 3. The GMD measured with the NanoScan-OPS was closer to those measured with the reference SMPS with R_{ps} values ranging from 0.96 to 0.99 (deviations ≤ 4%). A regression analysis for the polydispersed aerosol size measurements also shows that the NanoScan SMPS had almost perfect agreement with the reference SMPS (R^2 > 0.99; slope = 1.02). For the PAMS, the R_{ps} values ranged from 0.90 to 1.03 (deviations ≤10%). A regression analysis also shows that the PAMS had a poorer agreement with the reference SMPS (R^2 ~ 0.99; slope = 1.30).

Discussion

In the four monodispersed NaCl particle sizes of 30, 60, 100, and 300 nm tested, the particle number concentrations measured with the NanoScan SMPS compared favorably with those measured with the reference SMPS. A possible reason for good agreement between the NanoScan SMPS and the reference SMPS is that both device measurements rely on similar accurate sizing and counting. For the PAMS, number concentrations were within 18% of those measured with the reference SMPS for large monodispersed particle sizes of 100 and 300 nm, and this agreement can be considered as a reasonable comparability between the PAMS and the reference SMPS for these particle sizes; however,

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Table 3. Summary of polydispersed particle size measured by the NanoScan-OPS combined, PAMS, and the reference SMPS.

Concentration levels[a]	Reference SMPS		NanoScan-OPS combined			PAMS		
	Avg.GMD[b] (nm)	Avg.GSD[c]	Avg. GMD[b] (nm)	Avg. GSD[c]	$R_{ps,NanoScan\text{-}OPS}$[d]	Avg. GMD[b] (nm)	Avg. GSD[c]	$R_{ps,PAMS}$[d]
L	158 ± 0.85	1.69 ± 0.01	156 ± 0.98	1.69 ± 0.01	0.99	162 ± 1.15	1.76 ± 0.01	1.03
M	102 ± 0.54	1.94 ± 0.01	99 ± 0.68	1.95 ± 0.02	0.97	95 ± 0.89	2.09 ± 0.02	0.93
H	100 ± 0.52	1.91 ± 0.01	96 ± 0.57	1.93 ± 0.01	0.96	90 ± 0.84	2.02 ± 0.02	0.90

[a]Concentration levels: low, medium, and high.
[b]Average geometric mean diameter (avg. GMD ± standard deviation; n = 3 replicate tests).
[c]Average geometric standard deviation (avg. GSD ± standard deviation; n = 3).
[d]Polydispersed aerosol size ratio (R_{ps}) of the average GMDs between the portable device ($d_{NanoScan\text{-}OPS}$ or d_{PAMS}) and reference SMPS (d_{SMPS}).

concentrations measured with the PAMS showed poor agreement with the reference SMPS data for small monodispersed particle sizes of 30 and 60 nm with 22 and 25%, respectively, larger than those measured with the reference SMPS. A possible reason why the comparability between the PAMS and the reference SMPS varied based on the different particle sizes is that larger particle sizes (>100 nm) would carry more charges and mainly have double-charged particles while smaller particle sizes would mainly have single-charged particles (Mills *et al*., 2013). Therefore, particle charge correction and errors in sizing propagate to the number concentrations measured by each device would yield different concentration results. For all four monodispersed aerosol sizes, the handheld CPC showed a low agreement with the reference SMPS with the number concentrations within 30% of those measured with the reference SMPS. One possible reason for large difference between the handheld CPC and the reference SMPS is that the handheld CPC has a low accuracy with the manufacturer-reported accuracy of ± 20%.

Polydispersed size distributions measured by the NanoScan-OPS, PAMS, and the reference SMPS had similar trends for all three of the different concentration levels of low, medium, and high. The particle diameters decreased when particle concentration levels increased from low to high. A possible explanation is that the airflow rate to the suspension solution increased when particle concentration levels increased, resulting increasing forces to its nebulizer jets and producing smaller particles. Both particle concentration and size distributions measured with the NanoScan-OPS had almost perfect agreement with the reference SMPS in each concentration level. A possible explanation is that both NanoScan-OPS and the reference SMPS measurements rely on similar concentration levels of interest and similar accurate sizing correction.

Based on the summation of polydispersed particle concentration across the size range of 14–862 nm, the total concentrations and the GMDs measured by the NanoScan-OPS compared favorably with those measured by the reference SMPS with the deviations of concentration ratio ≤10% and the size ratio ≤4%. A possible explanation for good agreement between the NanoScan SMPS and the reference SMPS is that both measurements rely on the similar particle charge correction and errors in sizing propagate to the number concentration measured. For the PAMS, the GMDs measured by this device was a reasonable comparability with those measured by the reference SMPS with the deviations of the size ratio ≤10%; however, the summation of particle concentrations measured by the PAMS had poor agreement with those measured by the reference SMPS. Except for the high concentration level (deviations ≤13%), the particle concentrations measured by the PAMS were remarkably different compared with those measured by the reference SMPS in low and medium concentration levels (deviations of 36 and 20%, respectively). The reason the particle concentrations were remarkably different in low and medium concentration levels, but not for the high concentration level is unclear. Possible explanations are: (i) each instrument might have its own specific concentration levels of interest, but it might have some limitations to other concentration ranges and (ii) each instrument measurement relies on its own sizing, counting, and post-processing.

Conclusions

Three different portable instrument sets: the handheld CPC, PAMS, and NanoScan-OPS combined which can be used for measuring aerosol particles in workplaces were evaluated against monodispersed and polydispersed NaCl aerosols. The measurement capabilities of these portable instruments were compared to those of

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the reference SMPS. For the monodispersed aerosols, the particle concentrations measured with the NanoScan SMPS compared most favorably with those measured with the reference SMPS (deviations ≤13%), followed by the PAMS (deviations ≤25%), and the handheld CPC (deviations ≤30%). For polydispersed particles, the particle sizes and concentrations at three different concentration levels of low, medium, and high measured with the NanoScan-OPS compared most favorably with those measured with the reference SMPS (deviations ≤4% for particle size; deviations ≤10% for concentration). For the PAMS, the particle-size comparability between the PAMS and the reference SMPS was quite reasonable with the deviations within 10%; however, the polydispersed particle concentrations measured with the PAMS showed poor agreement with the reference SMPS data with the deviations within 36%. While further studies are needed to determine how to wear and operate these portable instruments in simulated workplaces or real working environments, this study provided the advantages and limitations of each portable instrument and therefore results from this study can be used, with appropriate caution, when selecting a suitable portable instrument for aerosol particle measurement in the workplace.

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