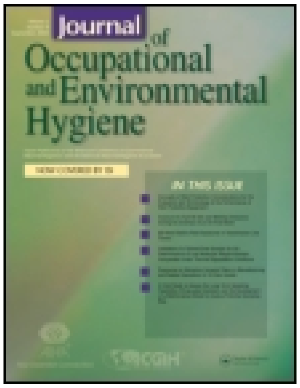

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We evaluated the robust, lightweight DiSCmini (DM) aerosol monitor for its ability to measure the concentration and mean diameter of submicrometer aerosols. Tests were conducted with monodispersed and polydispersed aerosols composed of two particle types (sodium chloride [NaCl] and spark-generated metal particles, which simulate particles found in welding fume) at three different steady-state concentration ranges (Low, <10^3; Medium, 10^3–10^4; and High, >10^4 particles/cm^3). Particle number concentration, lung deposited surface area (LDSA) concentration, and mean size measured with the DM were compared with those measured with reference instruments, a scanning mobility particle sizer (SMPS), and a handheld condensation particle counter (CPC). Particle number concentrations measured with the DM were within 16% of those measured by the CPC for polydispersed aerosols. Poorer agreement was observed for monodispersed aerosols (±35% for most tests and +101% for 300-nm NaCl). LDSA concentrations measured by the DM were 96% to 155% of those estimated with the SMPS. The geometric mean diameters measured with the DM were within 30% of those measured with the SMPS for monodispersed aerosols and within 25% for polydispersed aerosols (except for the case when the aerosol contained a substantial number of particles larger than 300 nm). The accuracy of the DM is reasonable for particles smaller than 300 nm, but caution should be exercised when particles larger than 300 nm are present. [Supplementary materials are available for this article. Go to the publisher's online edition of the Journal of Occupational and Environmental Hygiene *for the following free supplemental resources: manufacturer-reported capabilities of instruments used, and information from the SMPS measurements for polydispersed test particles.]*

Keywords CPC, DiSCmini, nanoparticles, SMPS, welding fume

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INTRODUCTION

Worker exposure to submicrometer aerosols is a major concern in many occupations and particularly so in welding. Welding fume typically consists of high concentrations of metal particles smaller than 300 nm,[(1)] which have been referred to as very fine particles.[(2)] The small particle size and presence of metals such as manganese, chromium, and cadmium contribute to the toxicity of welding fume.[(3)] Welding fume exposures have been associated with a variety of adverse health effects, including adverse pulmonary responses,[(4)] impaired neurological function,[(5)] lung cancer,[(6)] and cardiovascular disease.[(7)]

Personal monitoring with a direct-reading instrument (DRI) can be useful in associating high exposures to a contaminant with a particular task. A worker's time-weighted average exposure may then be lowered by modifying worker behavior, implementing engineering controls, or requiring personal protective equipment for high-exposure tasks. Photometers have previously been used to perform task-based exposure monitoring, such as in the assessment of personal exposure to dust among swine barn workers.[(8)] More recently, photometers have been recommended for use in identifying sources of nanomaterials in production facilities[(9)] and to monitor personal exposures to carbon nanotube-containing composite material from surface grinding.[(10)] Photometers are, however, limited to measuring particles larger than 300 nm. Consequently, they are inadequate for use in personal monitoring of the very fine particles that typically dominate welding fume exposures.

A variety of instruments can be used to measure the number concentration and size of very fine particles (examples in online Table S1). Traditionally, the size distribution of submicrometer aerosols has been measured with a scanning mobility particle sizer (SMPS), which electrically classifies particles by size and then counts them using condensation followed by optical detection.[11] The SMPS has excellent size resolution but takes several minutes for a single measurement and also requires a radioactive source to neutralize particles before sizing. Further, the SMPS is a bulky and expensive instrument, making it impractical for field use and limited to area rather than personal monitoring. Condensation particle counters (CPCs) are commercially available in a small, light, portable format, referred to as "handheld." Handheld CPCs can be used to rapidly measure (1-sec time resolution) total particle number concentration for submicrometer aerosols. The TSI 3007 handheld CPC (TSI Inc., Shoreview, Minn.) has been used to monitor particle concentrations in a variety of workplaces.[10,12,13] However, handheld CPCs provide no indication of particle size and are subject to counting errors when multiple particles are coincident in the optical detection region, which is common for high concentrations (>250,000 particles/cm^3).[14] Moreover, their large size and the fact that they must remain level to prevent working fluid from entering the optical circuitry presents a challenge for use in personal exposure monitoring applications.

Fierz et al.[15] introduced a new type of device for measuring the size distribution of submicrometer aerosols called the electrical diffusion battery. This benchtop-sized electrical diffusion battery used a positive corona discharge to charge particles entering the instrument. The charged particles then passed through an induction stage (or ion filter), a series of four diffusion stages—each consisting of a stack of metal screens—and a high-efficiency particulate air (HEPA) filter. The diffusion stages and the HEPA filter were each connected to an electrometer, which measured the charge of depositing particles. The smallest particles deposited on the screens in the first diffusion stage, whereas larger particles penetrated to subsequent diffusion stages or to the HEPA filter. The size distribution of the aerosol was then estimated from the electrical signals from the electrometers. Later, Fierz et al.[16] introduced a smaller, "backpack" version of this device. In this work, they suggested that only two or three stages were needed to achieve 10–20% agreement with the SMPS for number counting and sizing. In another effort, Fierz et al.[17] described the diffusion size classifier (DiSC), which was again a backpack-sized instrument identical to the electrical diffusion battery but with only one diffusion stage. Bau et al.[18] evaluated the DiSC, which they refer to as a commercial product sold as the meDiSC (Matter Aerosol AG, Wohlen, Switzerland). Bau and colleagues observed that the number concentration measured by the meDiSC differed from a reference CPC by greater than 30% for certain types of particles.

Further development by Fierz and colleagues resulted in miniature versions of the DiSC. Fierz et al.[19] described an instrument that they referred to as the "miniature DiSC" in the text but showed as the "miniDiSC" in a figure of the manuscript. The miniDiSC was a compact, rapidly responding, and robust miniature diffusion size classifier that was sold through the University of Applied Sciences Northwestern Switzerland. They recommended that the miniDiSC be used for aerosols with a mean diameter near 100 nm, concentration range of 10^3–10^6 particles/cm^3, and geometric standard deviation (σ_g) of about 1.7. The miniDiSC has been used to assess exposures to nanoparticles in nanomaterial facilities during simulated accident situations[20] and to ultrafine particles in ambient air.[21] For NaCl, oil [DEHS, Bis(2-ethylhexyl) sebecate], and soot aerosols, Fierz et al. reported that number concentrations measured with the miniDiSC were within ±30% of those measured with a CPC and an SMPS. Asbach et al.[22] observed similar results for aerosols containing mostly particles smaller than 300 nm. Fierz et al. identified that the miniDiSC underestimates particle size for narrowly distributed aerosols ($\sigma_g < 1.5$) and overestimates particle size for widely distributed aerosols ($\sigma_g > 2.1$). The overestimated geometric mean of particle diameters provided by the DiSCmini when compared with the SMPS is consistent with the findings from Meier et al.[23]

The DiSCmini (DM; V1.1, Matter) is a commercialized version of the handmade prototype miniDiSC.[24] The manufacturer reports that there should not be any significant differences in the performance of these two versions. We have been unable to identify published literature on the performance of the commercial version of the instrument. Moreover, the performance of either the miniDiSC or DiSCmini has not been evaluated for occupationally relevant nanoparticles, such as metallic particles common to welding fume.

Thus, the primary objective of the current study was to evaluate the performance of the DM particularly for very fine metal aerosols, like those typical of welding fume. We compared the measurements made with the DM with those made with a handheld CPC (3007, TSI, Inc.) and the SMPS (Sequential Mobility Particle Sizer, SMPS-C; Grimm, Ainring, Germany). Performance was evaluated in terms of lung-deposited surface area concentration, number concentration, and sizing for monodispersed and polydispersed salt and metal aerosols. The results of this evaluation will be useful for interpreting data collected with the DM at work sites where metal fume exposures are a hazard of concern.

MATERIALS AND METHOD

Shown in Figure 1, the experimental setup consisted of an air supply system, an aerosol generation system, and a measurement system. The air supply system was composed of an oil trap, a diffusion dryer, and a HEPA filter to remove oil-contaminants, humidity, and particles, respectively. The dry, clean air, controlled by a needle valve and monitored with a mass flowmeter (4146, TSI), was delivered to the test aerosol generation system. A nebulizer (Model Aeroneb Solo System; Aerogen, Galway, Ireland) was used to produce polydispersed NaCl-water droplets. The droplets were passed through a diffusion dryer to dry them. The nebulizer was turned on and off (1 Hz frequency and 10% duty cycle) to reduce the aerosol generation rate. A second set of tests used a spark discharge

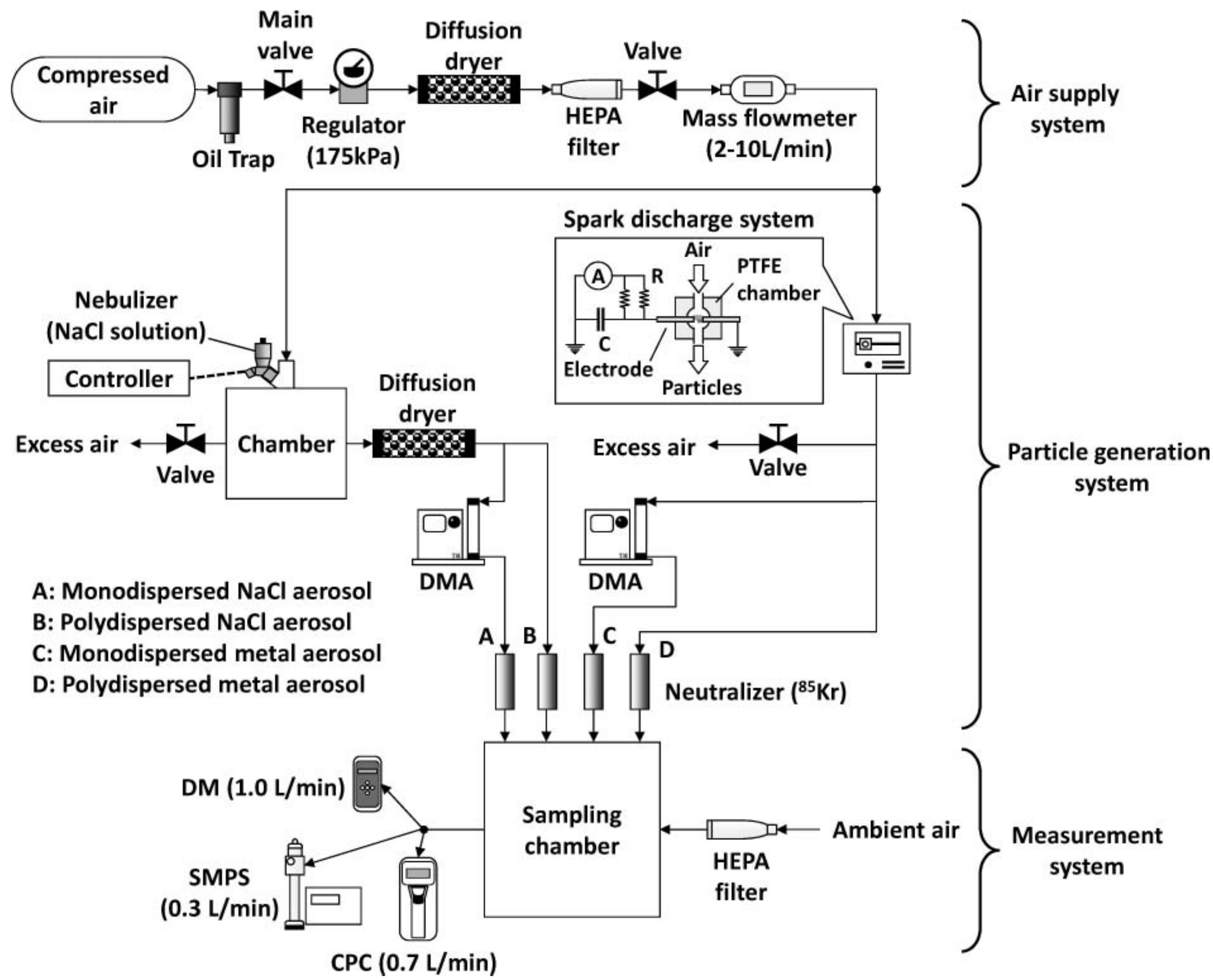

FIGURE 1. Experimental setup

system to generate polydispersed metal aerosols to simulate a welding fume. A spark discharge was formed in an air environment between two identical welding electrodes (Hard Surfacing Stick Electrodes—Overlay; Hobart, Troy, Ohio).[25] The electrical circuit included a resistance of 0.5 MΩ (two 1 MΩ resistors arranged in parallel), a capacitance of 1 nF, a loading current of 1 mA, and an applied voltage of 5 kV.

Monodispersed test aerosols were produced by passing the NaCl or metal aerosols through a neutralizer (3077A; TSI), then through a differential mobility analyzer (DMA, 3081; TSI). NaCl aerosols were classified to sizes of 30 nm, 100 nm, and 300 nm, and metal aerosols were classified to sizes of 30 nm and 100 nm. A second neutralizer (3054, TSI) was used to discharge the classified aerosol.

Both mono- and polydispersed aerosols were controlled in three different steady-state concentration levels: low: under 10^3; medium: 10^3–10^4; and high: over 10^4 particles/cm^3. Test aerosols were passed into a sampling chamber (4-L volume). The SMPS (0.3 L/min), CPC (0.7 L/min), and DM (1 L/min) were used to monitor the particle concentration and particle size distribution in the chamber. The SMPS consisted of a neutralizer (^{210}Po, 1U400; NRD LCC, Grand Island, N.Y.) and DMA (5.5-900; Grimm), and a CPC (5.402; Grimm). For the SMPS and CPC, a management software (#5.477/03–v1.34; Grimm) and an Aerosol Instrument Manager (7.2.0.0; TSI) were used, respectively. A data conversion tool (1.2; Matter) was used to obtain measurements of particle size and number concentration from the DM. Additional room air was allowed to pass through a HEPA filter into the sampling chamber to maintain ambient static pressure in the sampling chamber. The temperature and relative humidity of room air were 22.5 $\pm$ 3°C and 25 $\pm$ 5%, respectively.

For each test aerosol and concentration level, the SMPS was used to measure particle number concentration by size over three sequential 6-min sampling periods. The DM and CPC were configured to log measurements every second. The software from the SMPS manufacturer was used to obtain the total number concentration and geometric mean diameter (GMD) of the aerosol for each sampling period. For polydispersed aerosols only, SMPS-estimated alveolar lung deposited surface area concentration was calculated as:

$$\mathrm{LDSA_{SMPS}} = \sum_{i=1}^{41} \left(\mathrm{C_{SMPS,i}} \pi \mathrm{d^2_{SMPS,i}} \mathrm{D_{AL,i}} \right) \quad \textbf{(1)}$$

where C_{SMPS} is the number concentration, d_{SMPS} is the mid-point diameter, and D_{AL} is the alveolar deposition in the human respiratory tract for each channel (i) of the SMPS. This equation assumes that particles are spherical. $D_{AL,i}$ was computed using the following equation,

$$\mathrm{D_{AL,i}} = \left(\frac{0.0155}{\mathrm{d_{SMPS,i}}} \right) [\exp(-0.416(\ln \mathrm{d_{SMPS,i}} + 2.84)^2) + 19.11 \exp(-0.482(\ln \mathrm{d_{SMPS,i}} - 1.362)^2)] \quad \textbf{(2)}$$

The DM measurements corresponding to each of the three SMPS sampling periods were averaged to obtain three measurements of alveolar lung deposited surface area concentration, total number concentration, and GMD. The data from the CPC were processed similarly to obtain three measurements of particle number concentration.

The total number concentrations measured with the DM were compared with the reference number concentration from the CPC and the SMPS. The number concentration ratio (r_n) was defined as follows:

$$r_{n,CPC} = \frac{C_{DM}}{C_{CPC}} \quad \text{and} \quad r_{n,SMPS} = \frac{C_{DM}}{C_{SMPS}} \quad \textbf{(3)}$$

where C_{DM}, C_{CPC}, and C_{SMPS} are the total number concentration measured with the DM, CPC, and SMPS, respectively. The lung deposited surface area concentration ratio (r_{LDSA}) was defined as:

$$r_{LDSA} = \frac{\mathrm{LDSA_{DM}}}{\mathrm{LDSA_{SMPS}}} \quad \textbf{(4)}$$

where $LDSA_{DM}$ and $LDSA_{SMPS}$ are the alveolar lung deposition surface area concentration measured with the DM and SMPS, respectively.

The particle size measured with the DM and SMPS measurements were compared in two ways. First, a two-tailed, independent t-test was performed to test the hypothesis that the GMD measured by the DM was equal to that measured by the SMPS. Second, the ratio of particle size measured by the two instruments (r_s) was calculated as:

$$r_s = \frac{d_{DM}}{d_{SMPS}} \quad \textbf{(5)}$$

where d_{DM} and d_{SMPS} are the GMD measured with the DM and SMPS, respectively. A z-test was conducted to test the hypothesis that the ratio of size and concentration were statistically significant from unity at a significance level of 5%.

RESULTS AND DISCUSSION

Monodispersed Aerosols

A scatter plot of the total number concentration measured with the DM compared with that measured with the CPC is provided for tests conducted with monodispersed NaCl and metal aerosols in Figure 2. A summary of linear equations and R^2 values for total number concentrations measured by the DM and the CPC are listed in Table I. Number concentration ratios are provided in Table II, and results of sizing comparisons are provided in Table III. Ratios that are statistically different from unity are emphasized in bold text.

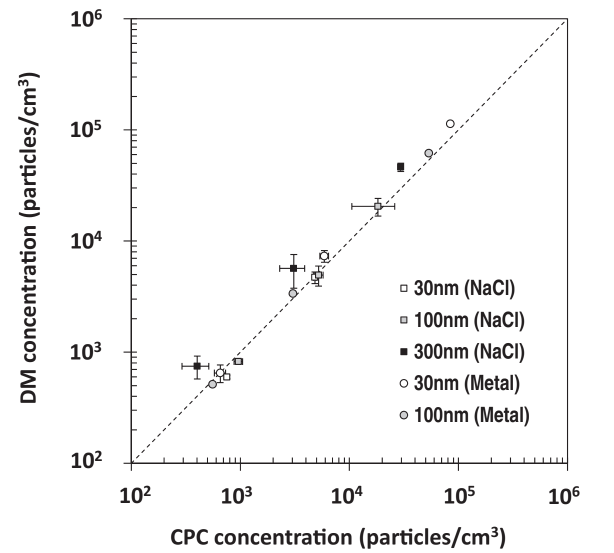

FIGURE 2. Total number concentration measured by the DM compared to that measured by the CPC for monodispersed NaCl and metal aerosols

In most monodispersed tests, the particle number concentrations measured with the DM compared favorably with those measured with the SMPS and CPC. As shown in Table II, number concentrations measured with the DM were within 35% of those measured with the CPC ($r_{n,CPC}$: 0.79 to 1.35), except for 300-nm NaCl aerosols. Concentration ratios for the SMPS were also near unity for 30-nm and 100-nm NaCl particles ($r_{n,SMPS}$: 0.81 to 1.17). However, the ratios were much higher than unity ($r_{n,SMPS}$: 1.29 to 2.27; all p-values <0.05) for the 300-nm NaCl and 30-nm metal aerosols. A measurement deviation of 35% is not unexpected given the manufacturer-reported accuracy of ± 20% for the CPC and ± 30% accuracy for the DM. These favorable results were found for monodispersed aerosols despite the fact that in calculating the number concentration with the DM, the geometric standard deviation (σ_g) assumed within the software of the DM is 1.7.[24] These results are consistent with those of Fierz et al.,[19] who observed that particle number concentrations measured with the miniDiSC were comparable to those made with a CPC regardless of the shape of the aerosol for 70-nm particles.

In all cases, the number concentration ratios estimated with data from the SMPS and CPC were similar, except for 30-nm metal particles ($r_{n,SMPS}$ ranged from 1.58–1.67; $r_{n,CPC}$ ranged from 0.99–1.35). The ratios estimated with the CPC values are likely to be most robust. The CPC simply counts each particle

TABLE I. Linear Equations and R^2 Values for Each Test for Each Instrument Used in Particle Number Counting

Test Particle	Test Aerosol	Particle Size (nm)	Equation[A]	R^2
Mono-dispersed	NaCl	30	$C_{DM} = 1.01\ C_{CPC} - 160$	1.000
		100	$C_{DM} = 1.15\ C_{CPC} - 620$	0.999
		300	$C_{DM} = 1.55\ C_{CPC} + 490$	1.000
	Metal	30	$C_{DM} = 1.35\ C_{CPC} - 440$	1.000
		100	$C_{DM} = 1.16\ C_{CPC} - 140$	1.000
Poly-dispersed	NaCl		$C_{DM} = 0.98\ C_{CPC} - 220$	1.000
	Metal		$C_{DM} = 0.94\ C_{CPC} - 240$	1.000

[A] C_{DM} and C_{CPC} are the total number concentration of DM and CPC, respectively.

as it enters the sensing zone of the instrument, whereas the SMPS measurement relies on accurate sizing, counting, and post-processing, including multiple charge correction. Particle sizing in the SMPS is influenced by particle shape, and errors in sizing propagate to the number concentration measured. The complex fractal shape of the metal aerosol may lead to erroneous sizing.

There were some notable deviations beyond the ± 30% manufacturer-reported accuracy of the DM where number concentrations measured by the DM were much greater than ± 35% different from those measured with the CPC. For 300-nm NaCl aerosols, number concentration ratios were substantially and statistically greater than unity ($r_{n,CPC}$ ranged from 1.55 to 1.86). These larger particles are capable of carrying more charge and could create measurement errors such as overcounting in the DM. A value of 1.7 for σ_g is used by the software internal to the DM used to compute particle number concentration. This assumption becomes increasingly problematical for monodispersed aerosols with a mean diameter larger than 100 nm, that are capable of carrying more charges. Similarly, Bau et al.[18] observed discrepancies of ± 74% in particle number concentrations measured with the meDiSC compared with those measured with the CPC.

Another possible reason is larger particles that are double-charged and can have the same electrical mobility as single-charged particles. The fractions of double-charged larger particles are about 5%, 8.9%, and 4.7% for 30, 100, and 300 nm, respectively. For 30-nm particle and 100-nm particles this fraction is negligible since the size difference of single-charged particles and double-charged particles is small and can be averaged by the DM. For example, a 30-nm single-charged particle has same electrical mobility as a 43-nm double-charged particle. However, for a 300-nm particle, 4.7% of the 510-nm double-charged particle can affect the overestimation of

TABLE II. Ratios of Particle Concentration for Tests with Monodispersed Aerosols

Test Aerosol Composition	d_{DMA}	Concentration Range[A]	$r_{n,SMPS} = C_{DM}/C_{SMPS}$ (SD)	$r_{n,CPC} = C_{DM}/C_{CPC}$ (SD)
NaCl	30	L	0.94 (0.06)	**0.79** (0.03)
		M	1.17 (0.20)	0.98 (0.09)
		H	—	—
	100	L	**0.81** (0.06)	**0.86** (0.05)
		M	0.96 (0.11)	0.95 (0.17)
		H	0.89 (0.14)	1.13 (0.43)
	300	L	**1.29** (0.25)	**1.86** (0.17)
		M	**2.21** (0.35)	**2.01** (1.07)
		H	**2.27** (0.23)	**1.55** (0.08)
Metal	30	L	**1.58** (0.25)	0.99 (0.06)
		M	**1.67** (0.21)	**1.24** (0.05)
		H	**1.58** (0.09)	**1.35** (0.01)
	100	L	**0.86** (0.03)	**0.92** (0.01)
		M	**1.05** (0.04)	**1.11** (0.00)
		H	1.01 (0.04)	**1.15** (0.00)

Note: Bold indicates reject H_0: R = 1 At $\alpha = 0.05$.
[A] Concentration ranges: low (L, $<10^3$ particles/cm^3), medium (M, 10^3–10^4 particles/cm^3), and high (H, $>10^4$ particles/cm^3).

TABLE III. Summary of Particle Size Measured by the DiSCmini (DM) and the SMPS Reference Instrument for Tests with Monodispersed Aerosols

Test Aerosol Composition	d_{DMA}	Concentration Range[A]	DM Avg. GMD (SD) nm	SMPS Avg. GMD (SD) nm	SMPS Avg. GSD	Size Ratio, r_s (SD)
NaCl	30	L	29 (3.8)	31 (0.44)	1.4	0.92 (0.11)
		M	46 (1.6)	36 (0.51)	1.6	**1.29** (0.09)
		H	—	—	—	—
	100	L	105 (1.7)	107 (0.67)	1.3	0.98 (0.02)
		M	112 (2.3)	114 (4.22)	1.3	0.98 (0.03)
		H	118 (2.2)	118 (1.46)	1.4	1.00 (0.03)
	300	L	256 (4.0)	199 (17.2)	2.0	**1.29** (0.09)
		M	232 (16.0)	272 (1.07)	1.4	**0.85** (0.06)
		H	263 (11.7)	258 (1.60)	1.6	1.02 (1.00)
Metal	30	L	38 (1.8)	40 (1.67)	1.9	0.96 (0.08)
		M	24 (0.9)	31 (0.10)	1.3	**0.76** (0.03)
		H	21 (0.0)	30 (0.06)	1.2	**0.71** (0.00)
	100	L	79 (1.2)	73 (2.32)	1.9	**1.08** (0.02)
		M	76 (0.4)	92 (0.65)	1.3	**0.83** (0.01)
		H	79 (0.5)	94 (0.44)	1.2	**0.84** (0.00)

Note: Bold indicates reject H_0: r = 1 at $\alpha = 0.05$.
[A]Concentration ranges: low (L, $<10^3$ particles/cm^3), medium (M, 10^3–10^4 particles/cm^3), and high (H, $>10^4$ particles/cm^3).

particle counting since it has large surface area and is over the size limit of DM.

A summary of particle size measured with the DM compared with that measured with the SMPS for monodispersed aerosols is provided in Table III. In general, the GMDs measured with the DM compared favorably with those measured with the SMPS, with r_s values ranging from 0.71 to 1.29. In many cases, however, the average GMD reported by the DM was statistically not equal to that reported by the SMPS (see bold r_n values in Table III). This finding relates to the fact that sizing each instrument was highly repeatable, resulting in low standard deviations observed for a given GMD measurement. For NaCl aerosols, the GMDs measured with the DM were significantly and substantially different for the medium concentration of 30-nm particles ($r_s = 1.29$) and for 300-nm particles at low ($r_s = 1.29$) and medium concentrations ($r_s = 0.85$). For monodipsersed metal aerosols, significant and substantial differences in the GMD measured with the DM and the SMPS occurred for the medium ($r_s = 0.76$) and high concentrations ($r_s = 0.71$).

Our results conflict somewhat with previous studies. Compared with the particle size measured with an SMPS, Fierz et al.[19] observed that the size measured with a miniDiSC was 18% smaller for an aerosol with a σ_g of 1.1. Bau et al.[18] observed that the meDiSC undersized monodispersed carbon and calcium carbonate particles larger than 300 nm. In contrast, we observed positive and negative deviations in sizing for monodispersed aerosols and therefore attribute these deviations to random error.

We observed notable deviations in the GMDs measured with the DM and SMPS from the particle size selected with the DMA (Table III). GMDs measured by both instruments were within ± 10 nm for a DMA setting of 30 nm, except for the DM at medium concentration of NaCl particles (GMD = 46 nm). For 100-nm tests, GMDs were consistently larger than the DMA setting for NaCl aerosols (105 nm to 118 nm) but smaller than the DMA setting for metal aerosols (73 nm to 94 nm). For 300-nm NaCl tests, measured GMDs were smaller than the DMA setting. The reason for these deviations is unclear.

Polydispersed Aerosols

Size distributions of polydispersed NaCl and metal test aerosols are shown in Figure 3. For NaCl aerosols, the GMD ranged from approximately 150–190 nm, and the σ_g ranged from 1.6–1.9. For metal aerosols, the GMD ranged from approximately 100–190 nm, and the σ_g ranged from 1.5-2.3 (online Table S2). The size distribution of the metal aerosols in this study was similar to that of a field study analyzing welding aerosols.[26,27] Zimmer[26] analyzed welding particles using transmission electron microscopy and the particles formed during welding ranged in size from 50–300 nm. Stephenson et al.[27] reported that welding produced an approximately lognormal particle mode with a 120-nm count median and a σ_g of 2.07.

The total number concentration measured with the DM and CPC compared with that measured with the SMPS for polydispersed NaCl and metal aerosols is shown in Figure 4.

TABLE IV. Ratios of Particle Concentration for Tests with Polydispersed Aerosols

Test Aerosol Composition	Concentration Range^A	$r_{n,SMPS} = C_{DM}/C_{SMPS}$ (SD)	$r_{n,CPC} = C_{DM}/C_{CPC}$ (SD)	$r_{LDSA} = LDSA_{DM}/LDSA_{SMPS}$ (SD)
NaCl	L	1.07 (0.09)	**1.06** (0.03)	1.09 (0.13)
	M	1.01 (0.02)	**0.89** (0.04)	**1.40** (0.03)
	H	0.93 (0.11)	1.04 (0.29)	**1.55** (0.15)
Metal	L	1.00 (0.01)	1.16 (0.15)	1.00 (0.06)
	M	**0.79** (0.07)	**0.83** (0.02)	0.97 (0.10)
	H	**0.82** (0.02)	**0.94** (0.01)	**1.10** (0.02)

Note: Bold indicates reject H_0: $r = 1$ at $\alpha = 0.05$.
^{A}Concentration ranges: low (L, $<10^3$ particles/cm^3), medium (M, 10^3–10^4 particles/cm^3), and high (H, $>10^4$ particles/cm^3).

A summary of particle number and LDSA concentration ratios is provided in Table IV.

For polydispersed NaCl or metal aerosols, the number concentration measured with the DM was within 21% of that measured with the SMPS and within 17% of that measured with the CPC (Figure 4, Table IV). The $r_{n,SMPS}$ values ranged from 0.79 to 1.07, and $r_{n,CPC}$ values ranged from 0.83 to 1.16. Ratios of less than unity (statistically not equal to unity) were observed for metal aerosol in medium and high concentrations. A summary of the linear equations and R^2 information for polydispersed particle number concentration tests is provided in Table I. Similar to the results of monodispersed particle tests, R^2 values indicated a highly linear relationship among the number concentrations measured by the DM and the CPC.

The observation that particle number concentrations measured with the DM compare favorably with reference instruments for polydispersed aerosols was expected. The polydispersed aerosols tested in this study (GMD from 150–190 nm, and σ_g from 1.6–1.9) were within the measurement range defined by the manufacturer of the DM. Similar results were obtained by Fierz et al.,[19] Asbach et al.,[22] and Meier et al.[23] for polydispersed aerosols that have GMD near 100 nm. However, Asbach et al. observed that number concentrations measured by the DM were low compared with those measured by reference instruments for polydispersed aerosols with a substantial number of particles larger than 300 nm. For polydispersed aerosols with a GMD smaller than 40 nm, Meier et al. observed that the DM overestimated the number concentration compared with the P-TRAK CPC. However, the lower size limit of the P-TRAK (~20 nm) is substantially larger than that of the CPC 3007 (~10 nm) used in this work. The ratio of LDSA concentrations ranged from 0.96 to 1.55. These findings were consistent with those described by Asbach et al., who observed that NaCl concentration was overestimated by the DM when compared to the SMPS and the LDSA from DM was closer to unity. They also observed that the overestimate of

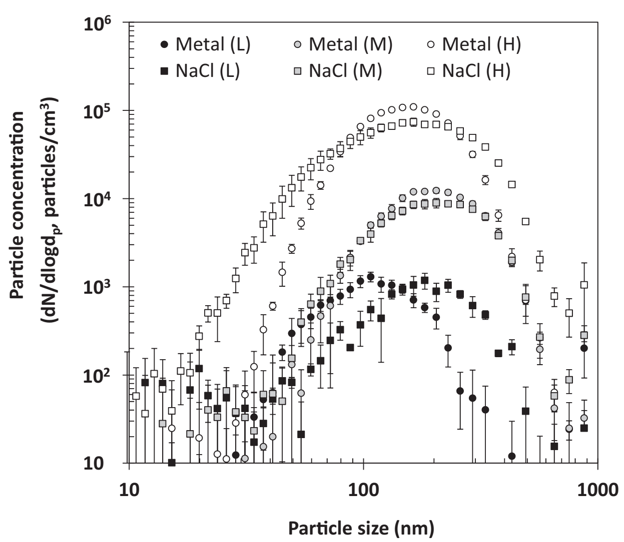

FIGURE 3. Size distributions of polydispersed test aerosols

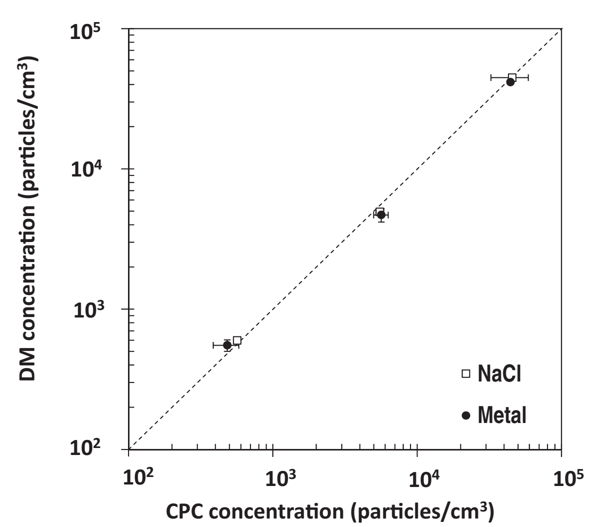

FIGURE 4. Total number concentration measured by the DM compared with that measured by the CPC for polydispersed NaCl and metal aerosols

TABLE V. Summary of Particle Size Measured by the DiSCmini (DM) and the SMPS Reference Instrument for Tests with Polydisperse Aerosols

Test Aerosol Composition	Concentration Range[A]	DM Avg. GMD (SD) nm	SMPS Avg. GMD (SD) nm	SMPS Avg. GSD	Size Ratio, r_s (SD)
NaCl	L	181 (10.3)	157 (8.5)	1.9	**1.15** (0.13)
	M	240 (2.2)	192 (2.1)	1.6	**1.25** (0.02)
	H	277 (9.1)	153 (7.9)	1.8	**1.81** (0.06)
Metal	L	107 (2.7)	107 (2.6)	1.6	1.00 (0.04)
	M	240 (2.2)	194 (4.2)	1.5	**1.24** (0.02)
	H	176 (3.9)	150 (2.3)	2.3	**1.17** (0.01)

Note: Bold indicates reject H_0: $r = 1$ at $\alpha = 0.05$.
[A]Concentration ranges: low (L, $<10^3$ particles/cm^3), medium (M, 10^3–10^4 particles/cm^3), and high (H, $>10^4$ particles/cm^3).

LDSA by the DM became greater with increased concentration for NaCl particles.

A summary of the particle size measurements for polydispersed NaCl and metal aerosols is shown in Table V. The GMD measured with the DM was equal to or larger than that measured with the SMPS with r_s values ranging from 1.00 to 1.81. There were significant differences between the GMD from the DM and the SMPS in all tests (p-value < 0.05), except for the metal particle test in the low concentration range ($r_s = 1.00$; p-value $= 0.98$). This difference was substantial for the tests conducted with a high concentration of NaCl particles ($r_s = 1.81$) but less so for other tests ($r_s < 1.25$).

The reason why the r_s values observed for the high concentration of NaCl particles were much higher than those observed in other tests is unclear. As mentioned earlier, a possible explanation is that large particles can carry more charges, which may cause the DM-measured particle size to be overestimated. As Fierz et al.[(19)] recommended, the DM should be used for aerosols with a mean diameter near 100 nm. From our work, we agree that the DM operates best with aerosols having a mean diameter near 100 nm but is also effective at measuring particle sizes near 30 nm. For particles larger than 300 nm, uncertainty with the DM can be increased and affect the size measurement capabilities. As shown in Figure 3, the test aerosols in this case included more particles larger than 300 nm compared with other test aerosols. Consequently, we recommend caution when measuring aerosols with a substantial number of particles larger than 300 nm.

Asbach et al.[(22)] identified similar performance for the miniDiSC with reported mean size matching reference instruments well when aerosols were dominated by particles within the 10 nm to 300 nm size range. They found that the GMD from the miniDiSC was overestimated compared to that measured by the fast mobility particle sizer.

CONCLUSION

In this study, the measurement capabilities of the DM were compared to those of a handheld CPC and an SMPS for submicrometer NaCl and metal aerosols. In the case of the monodispersed aerosols, the particle number concentration measured with the DM were within 35% of those measured with the CPC and SMPS with some exceptions. The greatest deviation was observed for aerosols composed of 300-nm NaCl particles, where the DM measured particle concentrations were approximately two times those of the CPC. The mean particle size measured with the DM was within 35% of that measured with the SMPS. For polydispersed particles, the number concentration was within 21% of those measured with the CPC and the SMPS for NaCl and metal aerosols.

The results from this study suggest that the DM can be useful to measure metal aerosols, such as welding fume, for personal task-based exposure monitoring, as well as many other occupational settings where very fine particles of interest are present. While further studies are needed to improve understanding of the DM, this work highlights the rapid response time and similarity of measurements to more common instruments, namely the CPC and SMPS.

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REFERENCES

1. **Jenkins, N., and T. Eagar:** Chemical analysis of welding fume particles. *Welding J. 84*:87 (2005).
2. **Heitbrink, W.A., D.E. Evans, T.M. Peters, and T.J. Slavin:** Characterization and mapping of very fine particles in an engine machining and assembly facility. *J. Occup. Environ. Hyg. 4*:341–351 (2007).
3. **Antonini, J.M.:** Health effects of welding. *CRC Criti. Rev. Toxicol. 33*:61–103 (2003).
4. **Antonini, J.M., M.D. Taylor, A.T. Zimmer, and J.R. Roberts:** Pulmonary responses to welding fumes: Role of metal constituents. *J. Toxicol. Environ. Health Part A 67*:233–249 (2004).

5. **Flynn, M.R., and P. Susi:** Neurological risks associated with manganese exposure from welding operations – A literature review. *Int. J. Hyg. Environ. Health 212*:459–469 (2009).
6. **Moulin, J.J.:** A meta-analysis of epidemiologic studies of lung cancer in welders. *Scand. J. Work Environ. Health 23*:104–113 (1997).
7. **Ibfelt, E., J.P. Bonde, and J. Hansen:** Exposure to metal welding fume particles and risk for cardiovascular disease in Denmark: A prospective cohort study. *Occup. Environ. Med. 67*:772–777 (2010).
8. **O'Shaughnessy, P.T., K.J. Donham, T.M. Peters, C. Taylor, R. Altmaier, and K.M. Kelly:** A task-specific assessment of swine worker exposure to airborne dust. *J. Occup. Environ. Hyg. 7*:7–13 (2009).
9. **Ramachandran, G., M. Ostraat, D.E. Evans, et al.:** A strategy for assessing workplace exposures to nanomaterials. *J. Occup. Environ. Hyg. 8*:673–685 (2011).
10. **Methner, M., C. Crawford, and C. Geraci:** Evaluation of the potential airborne release of carbon nanofibers during the preparation, grinding, and cutting of epoxy-based nanocomposite material. *J. Occup. Environ. Hyg. 9*:308–318 (2012).
11. **Wang, S.C., and R.C. Flagan:** Scanning electrical mobility spectrometer. *Aerosol Sci. Technol. 13*:230–240 (1990).
12. **Peters, T.M., W.A. Heitbrink, D.E. Evans, T.J. Slavin, and A.D. Maynard:** The mapping of fine and ultrafine particle concentrations in an engine machining and assembly facility. *Ann. Occup. Hyg. 50*(*3*):249–257 (2006).
13. **Curwin, B., and S. Bertke:** Exposure characterization of metal oxide nanoparticles in the workplace. *J. Occup. Environ. Hyg. 8*:580–587 (2011).
14. **Park, J., G. Ramachandran, P. Raynor, and S. Kim:** Estimation of surface area concentration of workplace incidental nanoparticles based on number and mass concentrations. *J. Nanopart. Res. 13*(*10*):1–15 (2011).
15. **Fierz, M., L. Scherrer, and H. Burtscher:** Real-time measurement of aerosol size distributions with an electrical diffusion battery. *J. Aerosol Sci. 33*:1049 (2002).
16. **Fierz, M., S. Weimer, and H. Burtscher:** Design and performance of an optimized electrical diffusion battery. *J. Aerosol Sci. 40*:152–163 (2009).
17. **Fierz, M., H. Burtscher, P. Steigmeier, and M. Kasper**: "Field Measurement of Particle Size and Number Concentration with the Diffusion Size Classifier, DiSC." SAE Technical Paper, 2008-01-1179, 2008.
18. **Bau, S., J. Jacoby, and O. Witschger:** Evaluation of the diffusion size classifier (meDiSC) for the real-time measurement of particle size and number concentration of nanoaerosols in the range 20–700 nm. *J. Environ. Monit. 14*:1014–1023 (2012).
19. **Fierz, M., C. Houle, P. Steigmeier, and H. Burtscher:** Design, calibration, and field performance of a miniature diffusion size classifier. *Aerosol Sci. Technol. 45*:1–10 (2011).
20. **Walser, T., S. Hellweg, R. Juraske, N.A. Luechinger, J. Wang, and M. Fierz:** Exposure to engineered nanoparticles: Model and measurements for accident situations in laboratories. *Sci. the Total Environ. 420*:119–126 (2012).
21. **Burtscher, H.**, **and K. Schüepp:** The occurrence of ultrafine particles in the specific environment of children. *Paediatric Respir. Rev. 13*:89–94 (2012).
22. **Asbach, C., H. Kaminski, D. Von Barany, et al.:** Comparability of portable nanoparticle exposure monitors. *Ann. Occup. Hyg. 56*(*5*):606–621 (2012).
23. **Meier, R., K. Clark, and M. Riediker:** Comparative testing of a miniature diffusion size classifier to assess airborne ultrafine particles under field conditions. *Aerosol Sci. Technol. 47*:22–28 (2013).
24. **Matter Aerosol AG:** *DiSCmini Diffusion Size Classifier Miniature Instruction Manual*, Rev 1.00. Wohlen, Switzerland: Matter Aerosol AG, 2011.
25. **Byeon, J.H., J.H. Park, and J. Hwang:** Spark generation of monometallic and bimetallic aerosol nanoparticles. *J. Aerosol Sci. 39*:888–896 (2008).
26. **Zimmer, A.T.:** The influence of metallurgy on the formation of welding aerosols. *J. Environ. Monit. 4*:628–632 (2002).
27. **Stephenson, D., G. Seshadri, and J.M. Veranth:** Workplace exposure to submicron particle mass and number concentrations from manual arc welding of carbon steel. *AIHA J. 64*(*4*):516–521 (2003).