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Evaluation of the DiSCmini personal aerosol monitor for submicrometer sodium chloride and metal aerosols

Jessica Breyan Mills
University of Iowa

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EVALUATION OF THE DISCMINI PERSONAL AEROSOL MONITOR FOR

SUBMICROMETER SODIUM CHLORIDE AND METAL AEROSOLS

by

Jessica Breyan Mills

A thesis submitted in partial fulfillment
of the requirements for the Master of
Science degree in Occupational and Environmental Health
in the Graduate College of
The University of Iowa

May 2013

Thesis Supervisor: Associate Professor Thomas M. Peters

Graduate College
The University of Iowa
Iowa City, Iowa

CERTIFICATE OF APPROVAL

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MASTER'S THESIS

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This is to certify that the Master's thesis of

Jessica Breyan Mills

has been approved by the Examining Committee
for the thesis requirement for the Master of Science
degree in Occupational and Environmental Health at the May 2013
graduation.

Thesis Committee: _____
               Thomas M. Peters, Thesis Supervisor

       _____
               T. Renée Anthony

       _____
               Nathan B. Fethke

It's amazing how you can get so far from where you planned, yet find it's exactly where you need to be.

Author Unknown

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ABSTRACT

This work 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 to 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 ($\pm$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.

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CHAPTER I

LITERATURE REVIEW

Nanoparticle Exposure Hazards in the Workplace

Nanoparticles

Various sources of nanoparticles (particles with all dimensions 100 nm or smaller) within a workplace can introduce many types of occupational hazards by the route of inhalation (Hinds, 1999; Schulte et al., 2008). Two types of nanoparticles are of general concern: engineered and incidental. Engineered nanoparticles (ENPs) have been used in the production of sporting goods, cosmetics, computer chips (Hawxhurst, 2007), stain-resistant clothing, and sunscreens (Nel et al., 2006). The number of workers exposed to nanoparticles is increasing with the emerging industries based on nanotechnology (Leskinen et al., 2012; Hansen et al., 2008). Estimates suggest approximately 2 million people worldwide will work with nanoparticles in an occupational setting by 2013 (Schulte et al., 2008). ENPs are defined as any material produced to have internal or external features smaller than 100 nm (Abe, 2011).

Incidental nanoparticles are unintentional forms of nanoparticles generated from natural sources, such as volcanoes and forest fires, and anthropogenic sources, such as internal combustion processes and welding (Methner et al., 2010). Anthropogenic sources are typically byproducts that are generated in high concentrations (Khalek et al., 2000; Elihn and Berg, 2009).

Welding is an occupational source of incidental nanoparticles of particular concern. Incidental particles such as welding fume introduce many occupational hazards due to the high concentrations and various chemical agents that are generated from a welding source (NIOSH, 1988). Knowledge of particle size and concentrations are important, primarily because welding is a hot process that generates high concentrations which may introduce very high incidental nanoparticle exposure to the worker during a

welding process (Jenkins and Eagar, 2005; Evans et al., 2008; Zimmer and Biswas, 2001). Approximately 600,000 workers in the United States are potentially exposed to welding fume (Zimmer and Biswas, 2001).

Workplace Scenarios Where Inhalation of Nanoparticles is a Concern

Manufacturing facilities where ENPs, such as carbon nanotubes and TiO_2, are used in production may expose workers to nanoparticles (Schmid et al., 2010; Maynard et al., 2004). Furthermore, occupational settings where biological and medicine research occur are another source of hazardous nanoparticles (Madl and Pinkerton, 2009). In laboratory settings where ENPs are handled, accidental scenarios should be considered. Walser et al. (2012) observed concentrations of gas phase ENPs in a laboratory after ventilation equipment suffered from a staged failure.

Industrial buildings where incidental nanoparticles are generated by processes such as welding, smelting, and grinding pose a great risk of exposure to high concentrations of numerous types of metal nanoparticles (Elihn and Berg, 2009; Stephenson et al., 2003). Elihn and Berg (2009) observed that hot processes, such as welding and laser cutting, generated higher particle number and surface area concentrations compared to colder processes. Furthermore, welding is considered among the most important industrial sources of nanoparticles. Consequently, welders are believed to experience elevated exposures to inhaled nanoparticles (Isaxon et al., 2009).

Toxicology of Nanoparticles

Inhalation is considered to be the primary route of exposure to nanoparticles (Curwin and Bertke, 2012). Particles from 0.1 to 0.01 μm in size deposit primarily in the alveoli (Mitsakou et al., 2007; Hinds, 1999). A fraction (~25%) of 0.01 μm sized particles deposit in the tracheobronchial region, primarily by diffusion. Furthermore,

particles that are 0.01 µm and smaller have an increased chance of deposition in the head airways by the diffusion mechanism (Hinds, 1999).

Once deposited, particles may be cleared or translocated to other parts of the body (Hinds, 1999). A large portion of the particles will be cleared from the body via natural clearance mechanisms, such as the mucociliary escalator and by alveolar macrophages (Hinds, 1999; Geiser et al., 2008). Upon deposition into the alveoli, smaller particles are capable of translocation to various parts of the lungs and other organs by passing through the alveolar membrane and are less likely to be cleared naturally (Oberdörster et al., 2002).

Particles deposited throughout the respiratory tract are capable of eliciting adverse health effects. Compared to larger (>100 nm) particles, nanoparticles may elicit a greater inflammatory pulmonary response which may induce greater toxicological effects (Oberdörster et al., 1994; Geiser et al., 2008). Dose metrics such as particle surface area have also been found to be an important component of inflammation in the lungs (Brown et al., 2009). Furthermore, the smaller surface area of nanoparticles make them more suitable for chemical reactions than a larger surface area, which can inhibit the immune system once inhaled or ingested (Oberdörster et al., 2005).

Many types of ENPs elicit adverse health effects once deposited into the respiratory tract. Carbon black and TiO_2 nanoparticles generate free radicals which induce oxidative stress and increase inflammation in the lung (Geiser et al., 2008; Madl and Pinkerton, 2009). Carbon nanotubes stimulate pulmonary inflammation and act as a catalyst for lung lesions (Lam et al., 2004). Long term exposure to these harmful particles causes chronic inflammation, which can lead to fibrosis of the lungs (Nel et al., 2006; Oberdörster et al., 1992). High number concentrations of nanoparticles are of particular concern because they can pose a higher health risk by overwhelming the body and compromising the immune system (Hinds, 1999; Oberdörster et al., 1992).

Incidental nanoparticles, such as welding fume, are another concern of exposure due to their toxicological contribution. Inhalation of welding fume is associated with many illnesses such as respiratory irritation, pulmonary illness, neurological outcomes, lung cancer, and decreased reproduction (Wu et al., 1996; Antonini, 2003; Flynn and Susi, 2009). The smaller particles found in welding fume contribute to the toxicity because of their capability to translocate, and promote inflammation by increasing macrophage and leukocyte production (Blanc et al., 1991; Klaasen and Watkins, 2010). Further epidemiological research and toxicological testing is needed to determine the hazard level of other types of incidental nanoparticles (Maynard et al., 2006; Schulte et al., 2009).

Epidemiological Studies of Nanoparticle Exposure

Although epidemiological studies are unavailable for ENPs (Schulte et al., 2009), numerous studies have investigated the association between exposure to incidental nanoparticles and adverse health outcomes. . Welders working with mild and stainless steel capable of generating metal oxide incidental nanoparticles are at a high risk of developing lung cancer (Hansen et al., 1996). Another study reviewed manganese exposure and neurological risks, such as Parkinson's disease, associated with welding fume containing manganese (Flynn and Susi, 2009). In this study, they concluded that the level of manganese exposure was dependent on the worker, and that arc welders are at a higher risk of manganese-induced Parkinsonism. Further epidemiological studies are needed regarding ENPs and incidental nanoparticles to determine the highest sources of exposure to nanoparticles, as well as the toxicological effects resulting from nanoparticle exposure.

Regulations

No current regulations exclusive to ENPs which protect workers are currently available (Methner et al., 2010; Leskinen et al., 2012; Schulte et al., 2010). However,

there are composition-specific permissible exposure limits (PELs) from the Occupational Safety and Health Administration (OSHA) that apply to ENPs, such as titanium dioxide (15 mg/m^3 for total particles) and silver metal (0.01 mg/m^3 for respirable particles) (OSHA). There are also International Standard Organization (ISO) standards regarding nanomaterials and nanotechnology, but these standards are not enforceable by OSHA. Exposure limits for ENPs have been proposed, and with the increasing trend in nanomaterial usage, these future limits may mitigate the exposure and hazards associated with nanoparticles (Murashov et al., 2011).

Many metals are listed with OSHA standards, but there is not a current exposure limit for total exposure of combined metals such as that found in welding fume (Zimmer, 2002; Berlinger et al., 2011). Individual components, specifically the respirable fraction (D50 = 4 μm), of welding fume must be monitored to ensure that specific threshold limit values (TLV) are not exceeded (ACGIH, 2011). In 1989, OSHA created a PEL of 5 mg/m^3 for welding fumes for an 8-hour time weighted average (TWA), but that limit has since been withdrawn (OSHA, 2013). In 1994, a TLV of 5 mg/m^3 for an 8-hour TWA was set for welding fumes not otherwise specified. However, in 2004, this exposure limit was removed. Both ENPs and incidental nanoparticles have different properties that may affect the behavior of the particle when measured by an instrument, as well as within the body, therefore, establishing regulations for each nanoparticle type can be a challenge (Leskinen et al., 2012).

Exposure Assessment

Filter-Based Measurement of Nanoparticles

Exposure assessment is an important aspect of determining the hazards associated with nanoparticles (Hansen et al., 2008). Personal exposures can be measured with traditional filter-based samplers. Personal sampling is typically done by using sampling pump that draws in air and collects particles on a filter within a 37-mm open-faced

cassette (Curwin and Bertke, 2012; Stephenson et al., 2003). However, using sampling media and a pump to acquire the mass concentration of a certain contaminant may not be the most efficient way to estimate exposure (Brouwer et al., 2004; Asbach et al., 2012). A disadvantage of mass concentration-based aerosol sampling is that temporal features of the exposure are not available , limiting the availability to associate periods of high or low exposure to the specific tasks or activities.

Filter-based measurements do not provide any information for personal sampling other than mass concentration. However, there are three metrics that should be considered when assessing exposure to nanoparticles: particle number concentration, size, and surface area. Particle number concentration is an important metric that is dependent on the generation process of the nanoparticles into the ambient air around a worker (Walser et al., 2012). Particle size has been noted as the most important factor to consider when monitoring airborne nanoparticles, such as incidental welding fume (Jenkins and Eager, 2005). A large portion of welding fume particles are nano-sized and may increase the risk of adverse health effects from increased penetration into the lungs (Jenkins et al., 2005; Antonini, 2003). Furthermore, surface area is another important factor because of its influence on adverse health effects (Madl and Pinkerton, 2009). Larger surface area has has a strong relationship with the inflammatory response in the lungs (Oberdörster et al., 1992).

Direct-Reading Instruments to Measure Nanoparticles

There is currently no agreement on what instruments should be used to measure nanoparticles in the workplace (Leskinen et al., 2012). Methods such as the use of direct-reading instruments may help to achieve a better worker exposure profile. The most common instruments used to measure nanoparticles are the condensation particle counter (CPC), the scanning mobility particle sizer (SMPS), the diffusion charger with electrometer (DC/E), and the photometer. The CPC operates by using the optical

measurement principle. Aerosol is drawn through an inlet, where alcohol is condensed onto the surface of the particles and supersaturates them. Once the aerosol is saturated with the alcohol, it passes through the condensing portion of the instrument where it is cooled, which causes particle growth by condensation, and finally the particles are optically detected (Hinds, 1999). The size range of the CPC (0.01 to 1.0 μm) makes it capable of measuring nanoparticles. Another positive characteristic of the CPC is that it has the ability to measure particles in rapidly changing concentrations (Leskinen et al., 2012). Zimmer and Biswas (2001) used a CPC to measure the particle number concentration of welding fume and also characterized the spatial and temporal variations of the aerosol. However, the CPC does not provide a particle size or surface areaand is not ideal for personal sampling, which is a disadvantage for task-based exposure monitoring. Additionally, high concentrations of particles can lead to undercounting when coincidence of particles occurs in the detection region.

The SMPS consists of a differential mobility analyzer (DMA) and a CPC. The SMPS operates on the basis of electrical and optical measurement principles and can obtain the particle diameter as well as the particle number concentration (Kulkarni et al., 2011). Aerosol is drawn into the SMPS, where it is neutralized according to the Boltzmann equilibrium charge distribution, and passes into an electrostatic classifier section inside the DMA. A thin layer of aerosol and sheath air surrounds the central rod of the DMA, which is positively charged (Hinds, 1999). Particles with a greater mobility diameter migrate to the central rod before they are passed through a gap, where they exit the DMA as singly-charged, monodispersed aerosol that are then optically counted by the CPC unit attached to the DMA. Subsequently, particles with a lesser mobility diameter do not reach the central rod, and exit beyond the gap and are filtered out. The SMPS is capable of measuring particles from 3 to 1000 nm, which is advantageous for the measurement for nanoparticles. Particle size distributions can be obtained using the SMPS for measurement of welding fume (Zimmer, 2002). However, the SMPS has a

slow response time (seven minutes), which is a problem when concentrations are rapidly changing. Other drawbacks of this instrument are that it is large, bulky, and expensive, making it nearly impossible to use as a task-based exposure monitoring device in field settings.

A photometer is another instrument used to measure incidental and ENPs (Hariri et al., 2012). The photometer operates by light scattering at fixed angles over the flow of particles to measure the mass concentration (Hinds, 1999). Photometers have been useful in monitoring engineered nanomaterials, such as carbon nanotubes, in production facilities (Methner et al., 2012). However, photometers are restricted to the measurement of mass concentration for particles larger than 300 nm. Thus, they are not sufficient for task-based measurement of incidental nanoparticles, such as welding fume.

Another instrument useful in the measurement of nanoparticles is the electrical diffusion battery. Fierz et al., (2002) developed an electrical diffusion battery, which operates by using a corona wire to charge particles. Once the particles are charged, they then diffuse onto four stages of metal screens and where the particle charges are drained from the particle and measured by an electrometer. The remaining airborne particles pass through a HEPA filter. The smaller particles deposit on the first screen, and larger particles deposit on the subsequent screens. A size distribution is estimated by the instrument once the electrical signals from the electrometers are measured. Further research efforts by Fierz et al. (2008) led to a smaller version of the electrical diffusion battery, the DiSC, which operated similarly to the diffusion battery, except that it has only one diffusion stage. The DiSC is a tabletop instrument that allows the user to monitor particle size and number concentration of aerosols. Fierz et al. (2008) used the DiSC to measure the incidental nanoparticle emissions near a highway to determine the number concentration and size of the particles emitted from vehicles.

The miniDiSC, a miniature diffusion size classifier, is a type of DC/E, and operates very similarly to the DiSC (Fierz et al, 2008). The ability of the miniDiSC to

measure particles from 10 to 300 nm, along with its small size, allows for personal exposure monitoring of nanoparticles (Fierz, 2011). The miniDiSC has been used to estimate workplace exposure in occupational settings (Fierz, 2011; Walser et al., 2012; Burtscher and Schüepp, 2012). Also, Walser et al (2012) used the miniDiSC to monitor the exposure of accident situations in laboratories that contain ENPs. The miniDiSC has also been used to monitor the distribution of incidental nanoparticles particles from traffic (Burtscher and Schüepp, 2012), and laboratory tests studying the characteristic size and concentration of incidental nanoparticles from diesel soot compared to reference instruments, such as the CPC and fast mobility particle sizer (FMPS; Asbach et al., 2012).

The commercialized version of the miniDiSC, the DiSCmini, was introduced in 2011 by Matter Aerosol (Matter Aerosol, 2011). This lightweight, robust, real-time instrument has the ability to measure particle number concentration, particle size, and lung-deposited surface area. The instrument operates by using a unipolar diffusion charger to charge the aerosol, then the smallest particles deposit onto two stages of diffusion screens, and the larger particles finally pass through a HEPA filter. The charges from the particles are measured at each stage by an electrometer. This instrument is useful for the measurement of ENPs and incidental nanoparticles, having the capability of measuring particles from 10 to 300 nm. However, no current publications have studied the new, commercially available instrument, and no known reports of lab or field testing of the instrument for metal particles that simulate incidental nanoparticles such as those present in welding fume.

Strategies to Use Direct-Reading Instruments

To perform exposure monitoring, strategies to use direct-reading instruments must be developed. Measuring personal occupational exposure to nanoparticles is a challenging task because of the lack of personal task-based monitoring instruments. Most

nanoparticle measuring instruments are large and bulky and are only suitable for workplace area monitoring, rather than personal exposure sampling (Elihn and Berg, 2009). A proper personal direct-reading instrument should be lightweight, robust, easily worn by a worker, and capable of measuring the nanoparticles in occupational settings where engineered and incidental nanoparticles are present (Fierz et al., 2011). Different job activities reflect multiple sources of exposures to nanoparticles, but the objective of task-based monitoring is to determine which job that generates the highest source of nanoparticles. An ideal nanoparticle instrument is needed that not only measures particle concentration and particle size but also particle surface area (Brouwer et al., 2004). A study examining ultrafine particle characteristics in an industrial plant monitored individual tasks by area sampling (Elihn and Berg, 2009). Consequently, this study determined that the particle number concentrations and particle sizes that were measured were not representative of the personal exposure of the worker. To provide a full understanding of worker exposure to nanoparticles, an assessment of the worker with direct-reading instruments that provide an exposure profile is needed (Ham et al., 2012).

To determine a worker's exposure profile, a task-based monitoring assessment can be performed. Task-based monitoring is different from typical full-shift monitoring, in that real-time results allow you to observe the variability within the task that the worker is performing (Ham et al., 2012). The exact point in the task where the highest exposures exist can be observed through monitoring the variability. Hazard mapping of a workplace using real-time instruments is another key component of task-based exposure monitoring, as it helps to determine the source of the nanoparticle exposure (Peters et al., 2006).

The lack of information regarding toxicity of nanoparticles has prompted the need for continuous exposure assessment (Marra, 2011). Continuous exposure monitoring requires the full 8-hour shift to be monitored to determine highest peaks of worker exposure. Most notably, worker exposure is dependent upon the material used in the

manufacturing process, energy put into the process, as well as the method that is being used to handle the nanoparticle source (Maynard et al., 2004; Ham et al., 2012). However, there are currently no direct-reading instruments to measure the mass concentration of nanoparticles in occupational setting where they may be of concern.

<div align="center">Shortcomings of Literature</div>

The DiSCmini is a newly commercially-available direct-reading instrument and has not been used to measure occupationally-relevant nanoparticles such as welding fume. Most studies using prototype versions of DiSCmini involved experiments in a laboratory setting with test aerosols, such as sodium chloride, or using the DiSCmini for the monitoring of ambient environmental nanoparticles. Using the DiSCmini to monitor the number concentration and size of particles generated from a typical occupational task such as welding, and then comparing those results to those from reference instruments, such as the SMPS and CPC, will help determine if this instrument is sufficient and reliable for future personal monitoring of nanoparticles.

<div align="center">Specific Aims</div>

This report is an attempt to lessen some of the shortcomings in the literature by evaluating the DiSCmini direct-reading instrument. The long term goal of this report is to accurately measure personal exposure by use of a newly commercialized direct-reading instrument in a way that can benefit a worker's health outcome.

The research work in this report strives to accomplish such goals by having accomplished the following aims:

1. Measure particle concentration, particle size, and particle surface area using a newly-commercialized direct-reading instrument for an occupationally-relevant aerosol, welding fume.

2. Compare the performance of the DiSCmini to a CPC and a reference instrument, the SMPS.

CHAPTER II

EVALUATION OF THE DISCMINI PERSONAL AEROSOL
MONITOR

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, which have been referred to as very fine particles (Jenkins and Eager, 2005; Heitbrink et al., 2007). The small particle size and presence of metals such as manganese, chromium, and cadmium contribute to the toxicity of welding fume (Antonini, 2003). Welding fume exposures have been associated with a variety of adverse health effects, including adverse pulmonary responses (Antonini, 2004), impaired neurological function (Flynn and Susi, 2009), lung cancer (Moulin, 1997), and cardiovascular disease (Ibfelt et al., 2010).

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 (O'Shaughnessy et al., 2009). More recently, photometers have been recommended for use in identifying sources of nanomaterials in production facilities, and to monitor personal exposures to carbon nanotube-containing composite material from surface grinding (Ramachandran et al., 2011; Methner et al., 2012). 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 may be used to measure the number concentration and size of very fine particles (examples provided in Table A-1). 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 (Wang and Flagan, 1990). 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 (one-second time resolution) measure total particle number concentration for submicrometer aerosols. The TSI 3007 handheld CPC has been used to monitor particle concentrations in a variety of workplaces (Methner et al, 2012; Peters at al., 2006; Curwin and Bertke, 2012). 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) (Park and et al., 2011). 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. (2002) introduced a new type of device for measuring the size distribution of submicrometer aerosols called the electrical diffusion battery. This bench-top-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. (2008) 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. (2008) 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. (2012) evaluated the DiSC, which they refer to as a commercial product sold as the meDiSC by Matter Engineering, Switzerland. They 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. (2011) described an instrument that they refer to as the 'miniature DiSC' in the text but show 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 (Walser et al., 2012) and to ultrafine particles in ambient air (Burtscher and Schüepp, 2012). For NaCl, oil [DEHS, Bis(2-ethylhexyl) sebecate], and soot aerosols, Fierz et al. (2011) reported that number concentrations measured with the miniDiSC were within ±30% of those measured with a CPC and an SMPS. Asbach et al. (2012) observed similar results for aerosols containing mostly particles smaller than 300 nm. Fierz et al. (2011) 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 DM when compared to the SMPS is consistent with findings from Meier et al (2013).

The DiSCmini (DM; V1.1, Matter Aerosol, Switzerland) is a commercialized version of the hand-made prototype miniDiSC (2011). 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 have 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 to those made with a handheld CPC (3007, TSI, MN, US) and the SMPS (Sequential Mobility Particle Sizer; SMPS-C, Grimm, 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 worksites where metal fume exposures are a hazard of concern.

Methods

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, MN, US), 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 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, US) (Byeon et al., 2008). 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, Shoreview, MN, US), then through a differential mobility analyzer (DMA; 3081, TSI, Shoreview, MN, USA). 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, MN, US) 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, NY, US) and DMA (5.5-900, Grimm, Germany), and a CPC (5.402, Grimm, Germany). For the SMPS and CPC, a management software (#5.477/03–v1.34, Grimm, Germany) and an Aerosol Instrument Manager® (7.2.0.0, TSI, MN, US) were used, respectively. A data conversion tool (1.2, Matter Aerosol, Switzerland) 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±3°C and 25±5%, respectively.

For each test aerosol and concentration level, the SMPS was used to measure particle number concentration by size over three sequential six-minute 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:

$$LDSA_{SMPS} = \sum_{i=1}^{41}\left(C_{SMPS,i}\ \pi\ d_{SMPS,i}^2\ D_{AL,i}\right) \tag{1}$$

where C_{SMPS} is the number concentration, d_{SMPS} is the midpoint 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,

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

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,

$$r_{n,CPC} = \frac{C_{DM}}{C_{CPC}} \ and \ r_{n,SMPS} = \frac{C_{DM}}{C_{SMPS}} \tag{3}$$

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:

$$r_{LDSA} = \frac{LDSA_{DM}}{LDSA_{SMPS}} \qquad (4)$$

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:

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

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 to 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 1. Number concentration ratios are provided in Table 2, and results of sizing comparisons are provided in Table 3. Ratios that are statistically different from unity are emphasized in bold text.

In most monodispersed tests, the particle number concentrations measured with the DM compared favorably to those measured with the SMPS and CPC. As shown in Table 2, 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 (Meier et al., 2013). These results are consistent with those of Fierz et al. (2011), 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 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 over-counting 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, which are capable of

carrying more charges. Similarly, Bau et al. (2012) observed discrepancies of ±74% in particle number concentrations measured with the meDiSC compared to those measured with the CPC. Another possible reason is larger particles that are double-charged and can have same electrical mobility as single-charged particle. 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 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 to that measured with the SMPS for monodispersed aerosols is provided in Table 3. 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 3). 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 previous studies. Compared to the particle size measured with an SMPS, Fierz et al. (2011) observed that the size measured with a miniDiSC was 18% smaller for an aerosol with a σ_g of 1.1. Bau et al. (2012) 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 3). 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.

<div align="center">Polydispersed Aerosols</div>

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 (Table B-1). The size distribution of the metal aerosols in this study was similar to that of a field study analyzing welding aerosols (Zimmer, 2002; Stephenson et al., 2003). Zimmer (2002) analyzed welding particles using transmission electron microscopy and the particles formed during welding ranged in size from 50-300 nm. Stephenson et al. (2003) 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 to that measured with the SMPS for polydispersed NaCl and metal aerosols is shown in Figure 4. A summary of particle number and LDSA concentration ratios is provided in Table 4.

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 4). 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 1. 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 to 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 in the best range for measurement by the DM. Similar results were obtained by Fierz et al. (2011) and Asbach et al. (2012) for polydispersed aerosols that have GMD near 100 nm. However, Asbach et al. (2012) observed that number concentrations measured by the DM were low compared to those measured by reference instruments for polydispersed aerosols with a substantial number of particles larger than 300 nm.

The ratio of LDSA concentrations ranged from 0.96 to 1.55. These findings were consistent with those described by Asbach et al., (2012), who observed that NaCl concentration was overestimated by the DM when compared to the SMPS and the LDSA from DM is closer to unity. The overestimation of LDSA increases with the increasing concentration in the lower concentration ranges of NaCl particles.

A summary of the particle size measurements for polydispersed NaCl and metal aerosols is shown in Table 5. 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 (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). These ratios were not equal to unity in all cases except for the test with the low concentration of metal aerosols.

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. (2011) 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 to other test aerosols. Consequently, we recommend caution when measuring aerosols with a substantial number of particles larger than 300 nm.

Asbach et al. (2012) 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. Meier et al. (2013) found that with the larger particle size range in polydispersed aerosols, the DM had a tendency to overestimate the number concentration when compared to the P-TRAK (an instrument similar to the CPC). These results are similar to our metal aerosols tests in the medium and high concentration ranges. Meier et al. (2013) also suggests that instrument cutoff diameters contributed to the difference in particle counts for each instrument.

<div align="center">Conclusion</div>

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, and in many other occupational settings where very fine particles of interest are present. While further studies are needed to improve understanding of the DM for its operating parameters and limitations, this work highlights the rapid response time and similarity of measurements to well-established instruments, namely the CPC and SMPS.
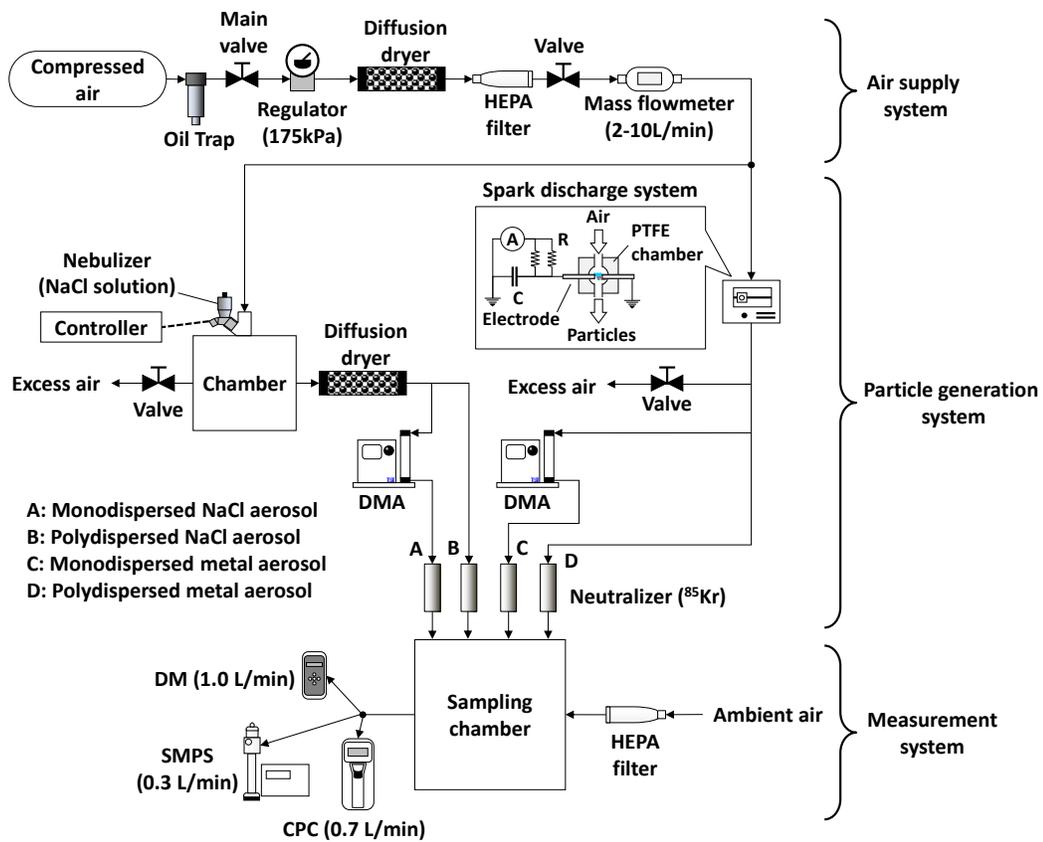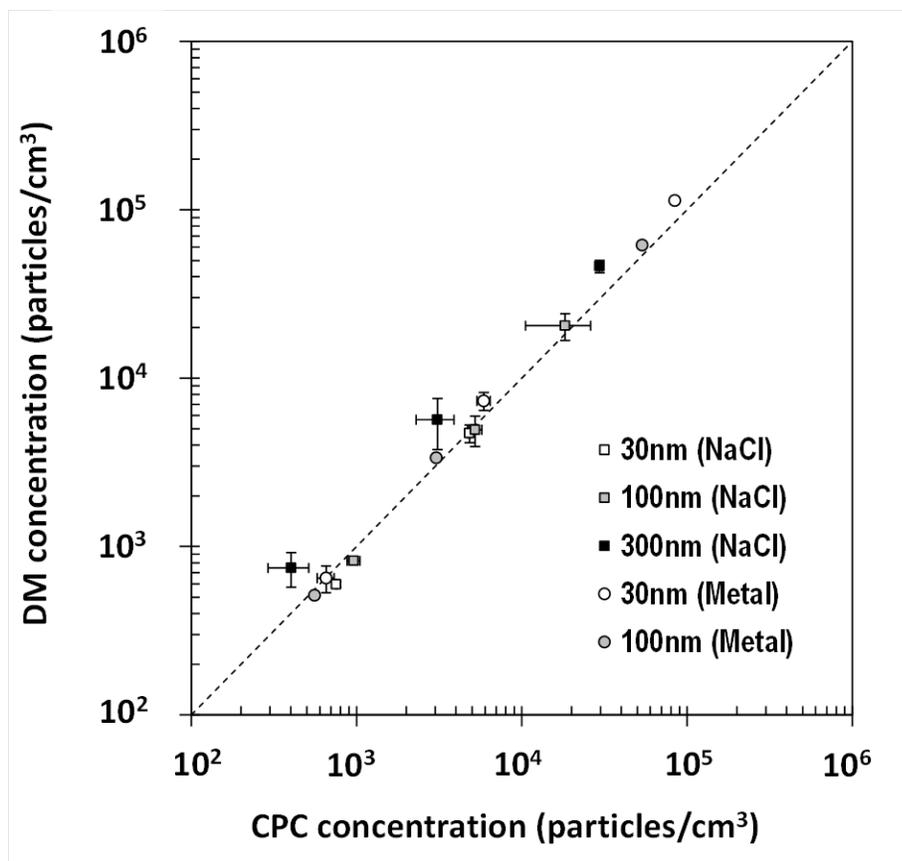
Figure 1. Experimental setup.

Figure 2. Total number concentration measured by the DM compared to that measured by the CPC for monodispersed NaCl and metal aerosols.
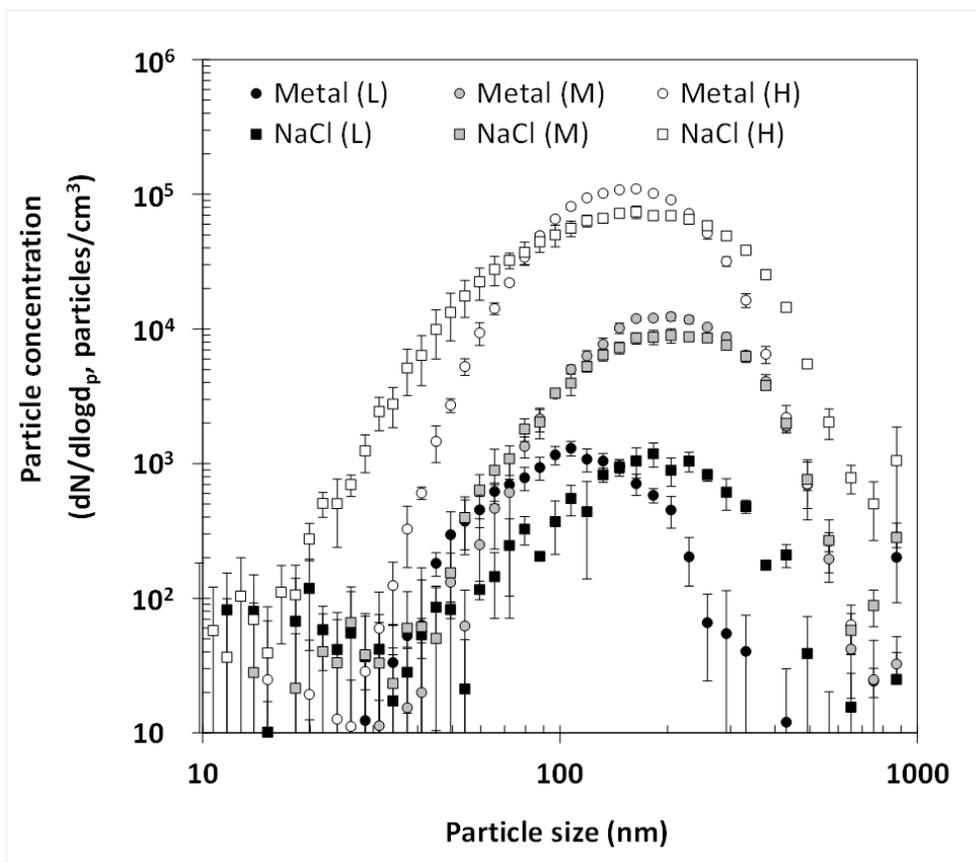
Figure 3. Size distributions of polydispersed test aerosols.
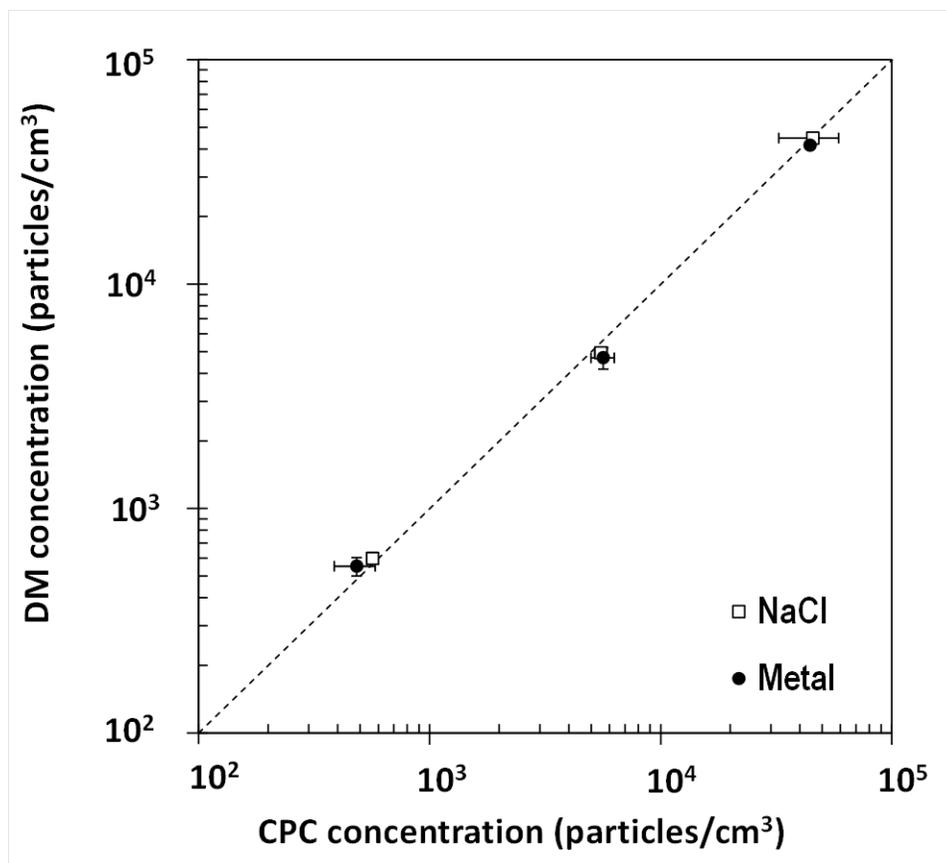
Figure 4. Total number concentration measured by the DM compared to that measured by the CPC for polydispersed NaCl and metal aerosols.

Table 1. 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	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

* C_{DM} and C_{CPC} are the total number concentration of DM and CPC, respectively.

Table 2. Ratios of particle concentration for tests with monodispersed aerosols. Bold numbers indicate reject H_0: r = 1 at α = 0.05.

Test Aerosol Composition	d_{DMA}	Concentration Range*	$r_{n,SMPS} = C_{DM} / C_{SMPS}$ (Std. Dev.)	$r_{n, CPC} = C_{DM} / C_{CPC}$ (Std. Dev.)
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)

*Concentration ranges are: 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 3. Summary of particle size measured by the DiSCmini (DM) and the SMPS reference instrument for tests with monodispersed aerosols. Bold numbers indicate reject H_0: r = 1 at $\alpha = 0.05$.

Test Aerosol Composition	d_{DMA}	Concentration Range[*]	DM Avg. Geo. Mean Dia. (Std. Dev.) nm	SMPS Avg. Geo. Mean Dia. (Std. Dev.) nm	Avg. Geo. Std. Dev.	Size Ratio, r_s (Std. Dev.)
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)

[*]Concentration ranges are: 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 4. Ratios of particle concentration for tests with polydispersed aerosols. Bold numbers indicate reject H_0: $r = 1$ at $\alpha = 0.05$.

Test Aerosol Composition	Concentration Range[*]	$r_{n,SMPS} =$ C_{DM} / C_{SMPS} (Std. Dev.)	$r_{n,CPC} =$ C_{DM} / C_{CPC} (Std. Dev.)	$r_{LDSA} =$ $LDSA_{DM} / LDSA_{SMPS}$ (Std. Dev.)
	L	1.07 (0.09)	**1.06** (0.03)	1.09 (0.13)
NaCl	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)
	L	1.00 (0.01)	1.16 (0.15)	1.00 (0.06)
Metal	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)

[*]Concentration ranges are: low (L, $<10^3$ particles/cm^3), medium (M, 10^3-10^4 particles/cm^3), and high (H, $>10^4$ particles/cm^3)

CHAPTER III

CONCLUSIONS

This study compared a newly commercially-available direct-reading instrument to two reference instruments: the CPC and the SMPS. Polydispersed particles were generated using NaCl particles nebulized from solution and simulated welding fume particles generated with a spark discharge system. For monodispersed particles, NaCl and metal aerosols were classified into three sizes (30, 100, and 300 nm) controlled in three different steady-state concentration ranges (10^3, 10^3-10^4, and $>10^4$ particles/cm^3). Particle number concentrations were measured by the DM and compared to the CPC. Particle size was measured by the DM and compared to the SMPS. LDSA was also measured by the DM and compared to the SMPS. A total of 24 test conditions were conducted.

Evidence from Chapter II suggests that the DM provides similar results to the CPC for particle number concentration, as well as similar size measurements compared to the SMPS data. For monodispered aerosols, the particle number concentrations measured with the DM were within 35% of those measured with the CPC and the SMPS. The greatest disagreement was observed for tests conducted with 300-nm NaCl particles, when the DM measured concentrations double those from the CPC. Geometric mean diameters measured by the DM were within 30% of those measured by the SMPS. For polydispersed particles, the DM showed a better agreement with the reference instruments. The DM measured within 21% of the CPC and the SMPS for both NaCl and metal aerosols. Geometric mean diameters measured by the DM were within 25% of those measured by the SMPS. However, for the case where there were a substantial amount of particles larger than 300 nm, the measurements from the DM exceeded the SMPS measurements by 25%. LDSA concentrations measured by the DM were 96% to 155% of those estimated by the SMPS.

This study highlights the performance of the DM compared to two reference instruments, the CPC and the SMPS. Overall, the data from the DM was within 35% of the reference instruments, except for in certain cases, and the accuracy of the DM was shown to be reasonable for particles 300 nm and smaller. However, when measuring particles larger than 300 nm, caution should be exercised, as error in the measurements may increase. The results of this research suggest that the DM is useful for the measurement of metal particles similar to those found in incidental nanoparticles such as welding fume. The real-time data, along with the accuracy given by this instrument also indicate that it would be useful for task-based monitoring situations where a profile of exposure is needed.

Future studies need to be conducted to validate the DM as a personal direct-reading instrument. The DM is an electrical instrument that is dependent upon the dielectric constant of material. Using the DM in other laboratory experiments where test aerosols with widely varying dielectric constants, specifically widely-used occupational nanomaterials would be beneficial. Since there is such a small amount of information regarding nanomaterials available, as well as little research conducted with the DM, this would help to lessen some of the shortcomings found in the literature. The DM should be compared to the CPC and SMPS for nanomaterials in a field study experiment. The continued evaluation of the DM in the field setting for personal task-based monitoring by monitoring exposure welding fume would strengthen understanding of how the DM operates.

Field studies designed to use the DM in task-based monitoring, where particle concentration, size, as well as surface area are measured, are likely to be highly informative. In such studies, the inlet tube of the DM may be positioned in the worker's breathing zone and the DM mounted on the workers belt. The real-time measurements made with the DM during the work shift could be related to tasks or processes in the

work environment through diaries or video monitoring. These data would provide information about the worker's exposure profile to nanoparticles.

The DM operated within the manufacturer's 35% error compared to both reference instruments for most cases. Therefore, we suggest that the DM is a useful tool in the measurement of nanoparticles, particularly incidental nanoparticles, such as those found in welding fume.

APPENDIX A: MANUFACTURER INSTRUMENT SPECIFICATIONS

Table A-1. Manufacturer reported capabilities for each instrument used.

Company Model	Grimm SMPS 5.402	TSI CPC 3007	Matter Aerosol DiSCmini 1.1
Measurement principal	Electrical Size Separation & Condensation with Optical Detection	Condensation with Optical Detection	Diffusion Charging with Electrical Detection
Size range (nm)	11-1083	10-1000	10-300
Concentration range (particles/cm^3)	0-10^7	0-10^5	20nm: 10^3-10^6 100nm: 5×10^2-5×10^5
Sampling flow rate (L/min)	0.3	0.7	1.0
Weight (kg)	DMA: 7.8 CPC: 11.5 Total: 19.3	1.7	0.7
Limitations	Large, bulky size & slow measurement time	Too large for personal monitoring	Less accurate than laboratory-grade instruments (±30%)
Cost (USD)	$60,000	$8,500	$15,000

APPENDIX B: POLYDISPERSED TEST INFORMATION

Information from the SMPS measurements for polydispersed test particles is shown in Table B-1. The average total number concentration, average geometric mean diameter and average geometric standard deviations for both, NaCl and metal particles, are listed. The standard deviation of the average total number concentration was lower for the metal particles when compared to the NaCl particles. Similarly, the average geometric standard deviation was lower for the metal particles.

Table B-1. Information for polydispersed test particles measured by the SMPS.

Test particle	*Conc. Range	Avg. Total number conc. (Std. Dev.) particles/cm^3	Avg. Geo. Mean dia. (Std. Dev.) nm	Avg. Geo. Std. Dev.
NaCl	L	560 (61)	157 (8.5)	1.9
	M	4880 (213)	192 (2.1)	1.6
	H	47900 (3020)	153 (7.9)	1.8
Metal	L	550 (47)	107 (2.6)	1.6
	M	5870 (194)	194 (4.2)	1.5
	H	50900 (630)	150 (2.3)	1.5

*Concentration ranges are: low (L, $<10^3$ particles/cm^3), medium (M, 10^3-10^4 particles/cm^3), and high (H, $>10^4$ particles/cm^3)

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