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Quantitative Analysis of Unique Deposition Pattern of Submicron Fe_3O_4 Particles Using Computer-Controlled Scanning Electron Microscopy

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This study was designed to optimize particle counting of a unique deposition pattern of iron oxide (Fe_3O_4) particles that were collected by a multidomain magnetic passive aerosol sampler (MPAS). Fe_3O_4 is paramagnetic with a high magnetic susceptibility, rendering high collection efficiencies. The MPAS was designed exclusively for measuring particle penetration through protective clothing. To quantify particle deposition by size, two counting methods were employed with a computer-controlled scanning electron microscope (CCSEM). Based on a sequential set of measurements at known coordinates, particles were quantified across particle clusters collected by individual magnets. Because all magnets were of equal dimensions and strength, the particle concentration per cluster across the entire MPAS substrate was expected to be relatively uniform. However, since individual CCSEM fields are extremely small compared with the full sample, a randomized counting approach was used to determine how many fields were needed to obtain a representative subsample. Results by the sequential method show that particle numbers were higher toward the edge of the cluster, dominated by smaller particles; moderate at the center, dominated by larger particles; and null at the corners. The results additionally show that counting by the random method was comparable with the sequential method and repeatable for particle counts ranging from 3 to 383 particles per field, or 409,565–52,287,826 particles per substrate, taking between 25 and 53 min, respectively. The results suggest that with the random method, the CCSEM provided a powerful tool for quantitative analyses of particle numbers with unique deposition patterns.

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Disclaimer: the findings and conclusions of this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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INTRODUCTION

A novel magnetic passive aerosol sampler (MPAS) with enhanced particle sampling efficiency has previously been developed (Jaques et al. 2011). The MPAS was exclusively designed for application in the aerosol man-in-simulant tests (MIST), also called protective ensemble systems level aerosol tests. The MPAS consists of a 28 mm diameter aluminum body with a thickness of 8.6 mm, a total of 186 tiny magnets (with about 140 on the collection area) arranged in an alternating N and S pole pattern, and a piece of sampling substrate above the magnets. Each magnet has a surface area of 1.5 mm × 1.5 mm and a thickness of 0.75 mm with a maximum magnetic strength of 2.3 kilogauss at the center of its surface. In nature, all magnets are dipolar, with one side defined as its north and the other as its south. Surfaces with opposite poles attract and adhere to each other, while like poles repel. The array of tightly packed small adjacent magnets have close interactions and consist of multiple and alternating magnetic poles that form a steep magnetic field gradient with an inhomogeneous maximum effective region (MER) between adjacent magnets of alternating polarity (Cavopol et al. 1995; McLean et al. 2001). Iron oxide (Fe_3O_4) particles are paramagnetic (magnetically susceptible) and become nonpermanent magnets in the presence of an electromagnetic field (Jackson 1999). The magnetic flux caused by a set of alternating positive and negative magnetic bodies produces attractive forces along the conjoining sides of square magnets. At each of the four corners where the square magnets meet, repulsive forces create a magnetic void, which was expected to greatly enhance the particle collection efficiency of the MPAS compared with nonmagnetic passive samples. These alternating inhomogeneous forces were expected to produce a

corresponding unique nonuniform deposition pattern of particles drawn to areas on the MPAS substrate that correspond with individual magnets.

Previous studies have used passive samplers to evaluate personal and regional exposures to aerosols (Vinzents 1996; Wagner and Leith 2001a–2001c; Yamamoto et al. 2006; Lagudu et al. 2011). However, in contrast to the MPAS, these samplers collect particles at low deposition velocities, and thus require relatively extensive sampling periods (typically, between 2 and several days) to achieve adequate amounts for quantification (Wagner and Leith 2001a–2001c; Yamamoto et al. 2006). Since a sampling time of less than 2 h for the MIST is optimal because human subjects are used (American Society of Testing and Materials [ASTM] 2006), and few particles may penetrate effective protective clothing (Gao et al. 2011), the previously developed MPAS was incorporated into this study.

To develop a reliable and statistically powerful quantification procedure, the deposition pattern first needed to be characterized. The challenge was that penetration of particles through protective ensembles results in a mass too low for quantification by most analytical methods, but which gave a number count that may be too high to effectually quantify by manual scanning electron microscopy (SEM) procedures. Manual SEM counting is very slow and tedious for quantifying samples with numerous particles or field sites, and typically measures across small SEM fields that may not represent the complete sample, ultimately giving rise to the need for an automated method. Thus, a computer-controlled scanning electron microscope (CCSEM; Hopke and Casuccio 1991; Mamane et al. 2001; Willis et al. 2002) was employed in this study for quantifying particles collected by the MPAS. Since the MPAS substrate collects particles in a nonuniform pattern across individual magnets, a reliable counting procedure for the CCSEM (Mamane et al. 2001; Willis et al. 2002) needed to be validated. Additionally, particle penetration through protective clothing can vary with size, and the MIST procedure measures penetration at numerous locations throughout the ensemble (ASTM 2006), which may greatly vary in concentration. Thus, CCSEM was selected to expedite analysis of numerous samples with an expected wide range of particle sizes and concentrations. However, since the particle deposition pattern was expected to be nonuniform, the CCSEM method was evaluated for a reliable quantification procedure. The objective of this study was to characterize the unique deposition pattern collected on the MPAS substrate and to optimize a particle quantification procedure by using the CCSEM.

METHODS

Particle Collection by the MPAS

Details of the MPAS, the aerosol generation, and its delivery system have previously been described (Gao et al. 2011; Jaques et al. 2011). Fe_3O_4 particles (Alfa Aesar 12962, Puratronic®, 99.997%, Ward Hill, MA, USA) were used for generating a challenge aerosol with a six-jet atomizer (Model 9306; TSI Incorporated, Shoreview, MN, USA) and delivered to the MPASs inside a recirculation aerosol wind tunnel (RAWT; Jaques et al. 2011). Fe_3O_4 particles were used because they are magnetically susceptible and have an enhanced attraction for magnetic surfaces, which ultimately enhances their deposition onto the MPAS (Hunt et al. 1995; Svoboda 2004). A benchtop rotational shaker (Innova 2300; New Brunswick Scientific, Edison, NJ, USA) was used to maintain particle suspension during the generation process. Two diffusion dryers, each with water traps (Model 3062; TSI Incorporated), were used to remove moisture. A neutralizer (Model 3012; TSI Incorporated) was used to minimize electrostatic effects. The particles were injected into the RAWT 1 m upstream of the fan, and excess air was exhausted to maintain static pressure within the tunnel. The recirculated aerosol produced a steady count median diameter (CMD) of 135 nm and a geometric standard deviation (GSD) of 2.2, as measured by a scanning mobility particle sizer [(SMPS) Model 3936; TSI Incorporated] (Jaques et al. 2011). A 25-mm, 0.1-μm pore size Isopore™polycarbonate filter (Millipore, Billerica, MA, USA), which is both smooth and minimum in low background interference to optimize viewing by SEM, was used as the collection substrate. The MPAS was suspended across a screen-backed sample holder in the direction of the wind and exposed to the recirculated aerosol between 5 and 30 min to generate samples with low, medium, and high surface area concentrations of particles for CCSEM analysis. Figure 1 shows the deposition pattern of Fe_3O_4 particles collected on the MPAS substrate. There are about 140 particle clusters across

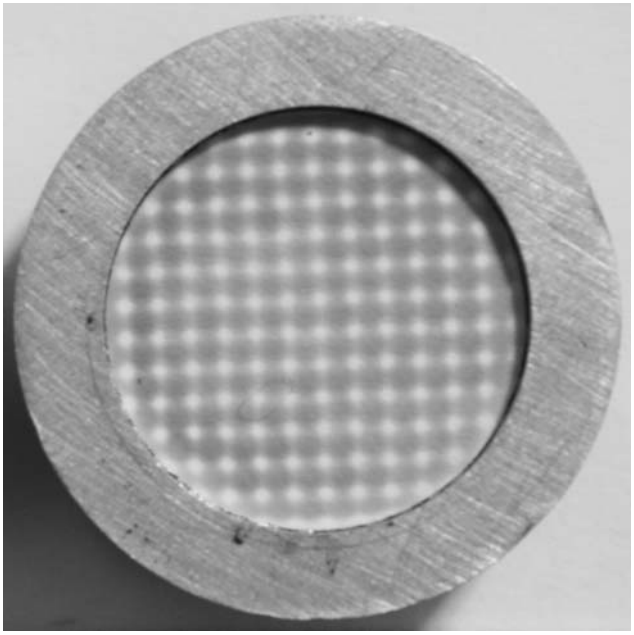


FIG. 1. Deposition pattern of Fe_3O_4 particles on polycarbonate filter collected by the MPAS.

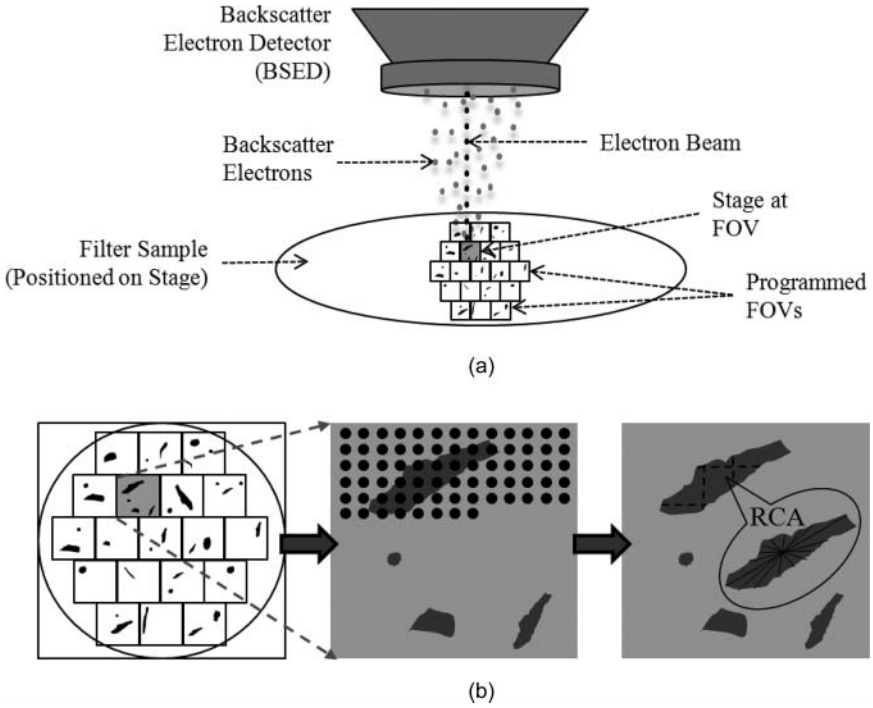


FIG. 2. Operation principle of CCSEM: (a) process of particle sizing and counting using a BSED; the sample and the stage are positioned to scan for particles at the BSED's field of view (FOV); and (b) three steps for locating the field and for sizing and counting particles: (1) stage moves to randomly selected or predetermined FOV; (2) beam is coarsely rastered across FOV; and (3) particles are identified by using the RCA, which draws 16 chords though the center of the particle for computing particle morphology.

the substrate, each of which was collected by a single magnet. Prior to analysis, the sample was lightly sputtered (Denton $Vacuum_{LLC}$, Model Desk V; Moorestown, NJ, USA) with gold for 40 s, enough to prevent electron charge interference, but not too much to lower the signal-to-noise ratio of the CCSEM analysis.

Particle Analysis by CCSEM

Figure 2 presents the CCSEM (ASPEX EXpress^{TM}, Delmont, PA, USA) automated quantification and measurement process for particle sizing and counting by way of a backscatter electron detector (BSED) (Hopke and Casuccio 1991; Mamane et al. 2001; Willis et al. 2002). The BSED gets its contrast from the average atomic number differences in the particle sample with an ultimate resolution of 25 nm. An integrated electron beam scanner and software is utilized to automatically and continuously measure multiple fields that have multiple particles (Casuccio et al. 1983). The electron beam scanner uses a coarse raster, a detailed scan, and a "rotating chord" algorithm (RCA) to measure the size and shape of the particles. This allows for rapid enumeration of particles by size. The instrument only spends time in collecting detailed data where particles are known to be present, rather than spending time in capturing and analyzing vast numbers of "empty" pixels. Since samples of submicron particles typically have much more empty space than occupied space, the CCSEM has a large analytical-speed advantage compared with the standard SEM. In this study, an energy-dispersive X-ray (EDX) spectrometer was not used, or necessary, because a known compound (Fe_3O_4) was exclusively delivered to the sample.

Sample Field Analysis by CCSEM

The CCSEM sample stage can be set as a rectangular, circular, or irregular area. It can be either programmed to sample several fields sequentially by specifying the coordinates, or set to sample randomly by using an integrated algorithm developed by the manufacturer, which selects field locations on the sample stub. The counting methods available in the CCSEM and the evaluation of their reliability are defined in much greater detail by Mamane et al. (2001). For establishing a statistically powerful sample set, there can be several fields per sample stage, as defined by the operator. For all MPAS substrates in this study, to optimize the resolution of particles between 80 and 550 nm, the electronic beam power was set to 20 keV, and the magnification was set to 10,000×. At these settings, the resultant area of each field was 0.0023 mm^2, while the full substrate area and the number of fields per substrate area evaluated varied between 2.25–177 mm^2 and 25–470 particles/field, respectively. The backscatter emissions projected by the Fe_3O_4 particles and polycarbonate substrate produce a signal ("sample") current that is electronically displayed as a nonunit line signal ("video image"). The emission signal of a Faraday cup is amplified to 4

nA to normalize the backscatter emission output of the CCSEM at the same beam power and magnification used for substrate analysis. The video line image projected by the particles and background is set low enough to maintain a threshold that does not accepts emissions by background noise, but high enough to accept emissions by the smallest particles that are visually observable at optimal working distances established in the manual calibration mode. If it was set too low, background emissions may be digitally interpreted as small particles.

Spatial Distribution Across the MPAS Substrate

To visually predetermine the spatial deposition pattern of particles, a set of substrates with a relatively high surface density of particles was evaluated. The images were projected at low magnification (25× and 50×) and set to a high brightness-to-contrast ratio. One MPAS substrate was sprinkled with Fe_3O_4 stock powder for low-resolution observation and a second was exposed to submicron particles in the RAWT for detailed observation. To evaluate the spatial variation of particles collected by individual magnets (dipoles) and the full array of MPAS magnets (multipoles), the CCSEM was programmed to sequentially measure and count particles within and between clusters of particles collected by individual magnets across a grid pattern (both 5 × 5 and 7 × 7). By visualizing a cluster at low magnification (25×), the magnet's corners were identified. Parallel and perpendicular lines were projected though the corners of adjacent clusters to form a coordinate grid. The "x"- and "y"-axis grid lines were evenly spaced along and across the vertical and horizontal sides of the defined square. The CCSEM was programmed to sequentially measure adjacent fields, along the top row, from left to right, followed by the second to the fifth or seventh, depending on the grid dimensions. The areal concentration of particle counts for each field within each of the six clusters was compared for differences by pairing data separately by columns and rows. An *F*-test was used to determine whether the variances were homogeneous, and a two-way analysis of variance (ANOVA; Microsoft Office Excel 2007) was used to evaluate their spatial uniformity.

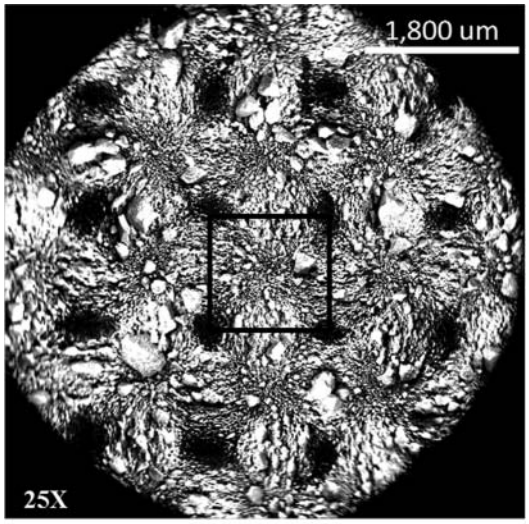
Particle Quantification by Random Method

A random counting method was used to evaluate the reliability in particle sizing and counting (Mamane et al. 2001; Willis et al. 2002). The particle size and concentration data quantified for each individual cluster by the random counting method was compared with the quantification results produced by the sequential grid counting method. To accurately evaluate the repeatability and minimum counts per field that could be quantified, at a range of particle surface densities, the precision of the random method was evaluated and the minimum number of fields required to reach a stable moving-concentration average was determined, respectively. The particle size distribution and areal number concentration were compared between the sequential and the random methods. Substrates with low and high loading were evaluated for the minimum number required to achieve a repeatable result.

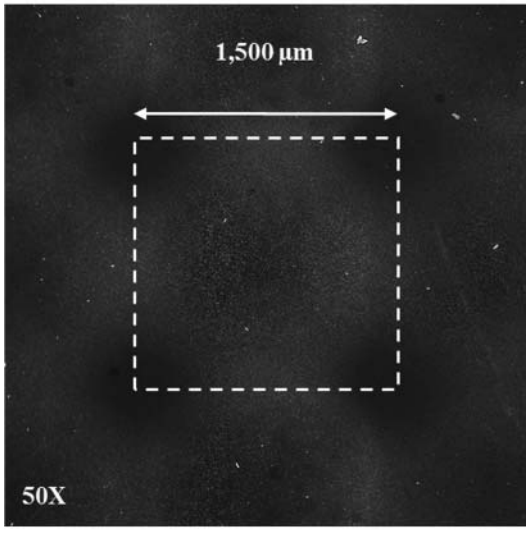
RESULTS AND DISCUSSION

Spatial Distribution Across the MPAS Substrate

Projected at low magnification, two micrographs of two separate sets of clusters collected onto polycarbonate substrate for the purpose of demonstrating the magnetic attraction of particles at a gross scale is presented in Figure 3. Figure 3a is an image of supermicron Fe_3O_4 particles that were sprinkled on the surface of the substrate, and Figure 3b is from an MPAS sample exposed to submicron particles in the wind tunnel. Borders are drawn on



(a)



(b)

FIG. 3. Low magnification SEM images of particles clustered about individual MPAS magnet as (a) a supermicron Fe_3O_4 powder sample and (b) an MPAS sample of Fe_3O_4 particles. Borders show collection boundaries of a cluster collected by single magnet with dark areas as magnet's corner.

each substrate to show the boundaries of what is expected to be of a cluster of particles collected by an individual magnet. In contrast to the small particle sample, the purpose of the large particle sample was to visually enhance the deposition pattern of single particles over a wide area at a low magnification and at a high video image contrast. However, the deposition pattern of the larger supermicron particles was not expected to fully reflect what would occur with submicron particles, which have much less mass and, in a nonmagnetic boundary region, deposit primarily by diffusion. Instead, over the MPAS substrate, the deposition of supermicron particles is, both, influenced by their inherent inertia and the greater proportion of induced magnetic domains on larger particles, which form suspended particles with enhanced magnetic susceptibility (Hunt et al. 1995; Svoboda 2004). Thus, the deposition pattern of the substrate with the larger particles was expected to visually show a greater fraction of particles deposited over the areas of a magnet with a greater magnetic field strength.

At a magnification of 25× (Figure 3a), the large particle image shows a general pattern of particle clusters in grid form across the MPAS substrate. Concentrations appear to be near zero at the corners of each cluster, but increase away from each corner toward the edge and middle of each cluster with fewer toward the center. While the corners mostly had no particles, it appears that larger particles were along the edges and smaller ones were at the center of each magnet. Additionally, the pattern between magnets is not completely consistent, with some magnets showing larger particles toward what is assumed to be groups of particles collected by the center of each magnet.

In contrast, the substrate with nanosized Fe_3O_4 particles appears as a cloud, because they are too small to be seen as individual particles at low magnification. As with the powdered substrate (Figure 3a), it shows darker and brighter areas. The darker areas are expected to be where particles were not collected, while the increasing brighter areas are assumed to be proportional to the density of particles collected. Additionally, the formed clusters, shown on both magnets, present themselves as an array of magnets (multipoles) (Figures 1 and 3) with the corners (areas without particles) assumed to be the four points of each square magnet.

Figure 4 shows contour plots of particle count and CMD for two representative clusters acquired by the sequential grid

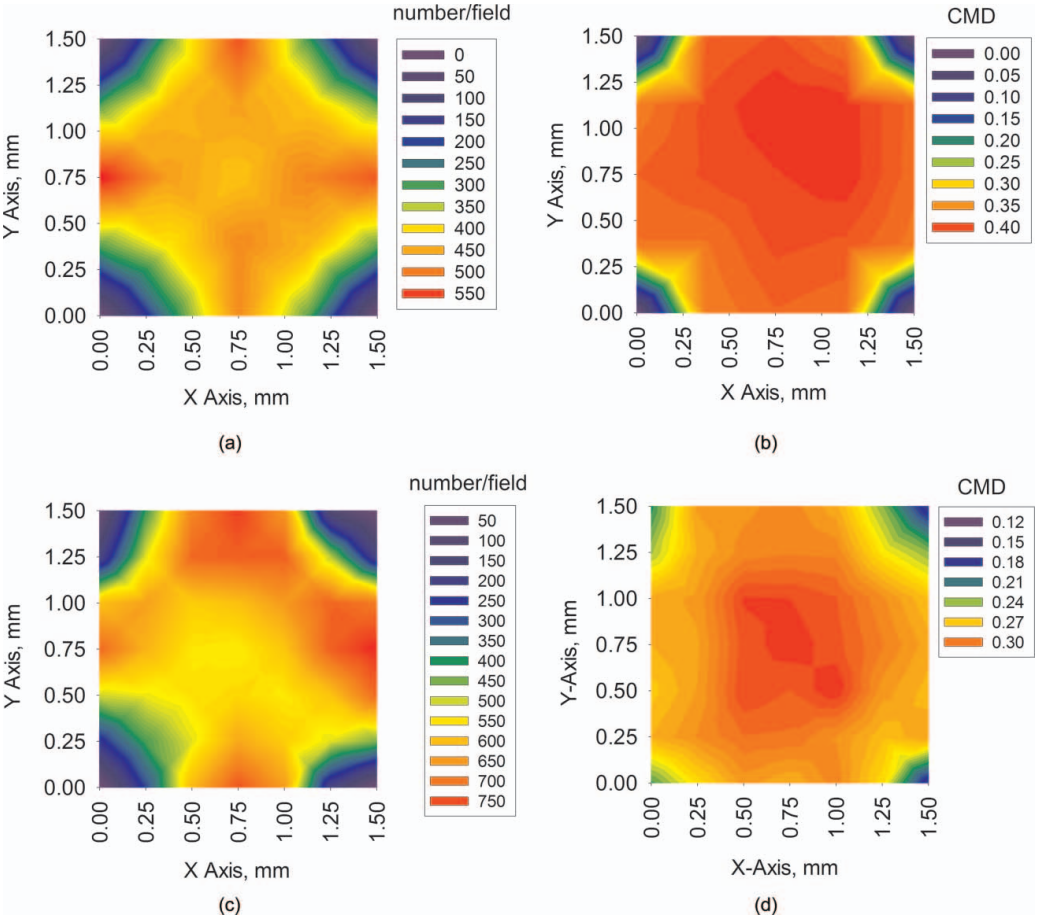


FIG. 4. Contour plots of particle number per field, and corresponding CMD for two separate clusters measured by the sequential grid counting method, with a 7 × 7 grid totaling 49 fields. Clusters are paired as number per field and particle size: (a) Cluster 1 (number/field); (b) Cluster 1 (CMD); (c) Cluster 2 (number/field); and (d) Cluster 2 (CMD).

method. They reflect that the greatest number of particles are collected at the edge of each magnet, less are in the area of its center, and close to none at the corners, while the largest particles tended toward the center and the smallest toward the edge. Six clusters (three scanned as 7×7 grids, and three scanned as 5×5 grids) were evaluated. An F-test, pairing data separately by columns and rows, showed that variances were significantly different from each other. This is clearly because of the extreme low particle count at the corners of each cluster. A two-way ANOVA test, which assumes unequal variances, showed that the surface particle count of the fields within each cluster was also significantly different from each other ($p < 0.05$). For five of the six clusters, the CMDs were also significantly different from each other ($p < 0.05$). These results quantitatively show that the particle number and size were not spatially uniform within each cluster. Previous work showing the increased effect of a steep magnetic field gradient on increased neural action potentials (Cavopol et al. 1995) suggests that the deposition of more particles toward the edge may be due to the effect of the steep magnetic field gradient in this area where magnets of opposite poles meet. Haverkort et al. (2009) have shown that capture efficiency increases with decreasing drag force so that smaller particles will be collected preferentially in the areas of highest field strength. The motion of the particles is governed by the balance between the magnetic attraction and the drag force on the particle. The drag force is related to the particle diameter, so the mobility of the particle, B (the relative ease of producing steady motion for a particle), is inversely related to the diameter. The terminal velocity for a particle in an external field is then the product of the force times the mobility (Vts = FB). Thus, for the same force, smaller particles will have a higher velocity. Particles will tend to follow lines of the highest field strength and these will come from the discontinuities at the edge of the magnets.

Prior to determining a quantification method designed to produce representative size and number measurements across the MPAS substrate, the uniformity of these unique deposition patterns across individual magnets needed to be evaluated across the entire MPAS substrate. To assess this, particles were randomly quantified within several fields, covering a large fraction of the substrate. Here, the CCSEM was programmed to randomly locate and measure particles across 56% (177 mm^2) of the sampling area of the MPAS substrate, equivalent to about 78 magnets. The sizes of 29,472 ± 339 particles ($N = 3$) were enumerated, requiring 476 fields. Figure 5 shows the frequency distribution of particles per field. The number of particles per field ranged between zero, which was generally at the corners between two magnets of the same polarity, and 133, which was generally along the edge between opposing polarity magnets. The spatial distribution of particles across the MPAS substrate showed that particles per field had a relatively wide distribution, with 90% (430 of 476 fields) of the fields having between 7 and 100 particles. The highest frequency of fields with the same number of particles was 11, giving 74 particles per field. Conversely, if all particles were evenly spaced, then 100% of the fields would have identical particle numbers. Evaluation of the distribution of particles per field provides an approach for comparing counting protocols. From these results, it may be expected that regardless of the number of particles per field, the average number of particles per field across the MPAS substrate would track a similar pattern, because the average magnetic field strength across each magnet would be similar. Thus, on average, the proportion of particles per field across the entire MPAS substrate should be consistent. Counting protocols with fewer fields and, thus, a shorter sampling time, could be compared to show the same trend, although not necessarily the same concentration per field. If similar in trend, but with less particles per field, then the number of fields analyzed could be considered to provide a sufficient population to have a statistical power equivalent to a more highly concentrated sample.

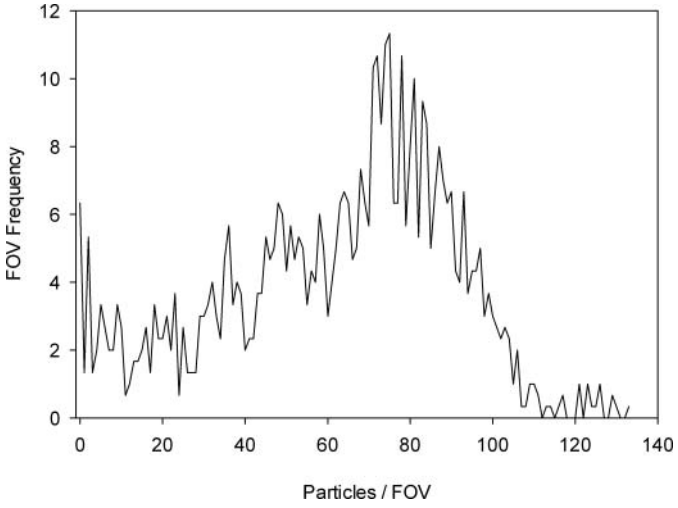


FIG. 5. Frequency distribution of particles per field using the random counting method.

Quantification Strategy of Particles by CCSEM

Random measurement of particles within fields across the majority of the MPAS substrate indicates uniformity between clusters of particles, but which demonstrate a nonuniform pattern within each cluster. Thus, the random counting method was evaluated as a possible tool for acquiring a representative sample count. The random counting method was compared with the sequential grid counting method by programming the CCSEM to measure and count particles using the same number of fields (7×7) within the same cluster evaluated by the sequential grid counting method. Figure 6 presents the size distribution and precision (as the percent coefficient of variation, CV%) between replicates ($n = 5$) by both the sequential grid and the random methods (about 22,000 particles were analyzed). The measured size distributions are nearly identical; a two-way ANOVA test showed no significant differences for particles between 80 and 750 nm ($p > 0.1$). Also, the results show a high reliability between the two methods, with a CV% less than 5% for particles

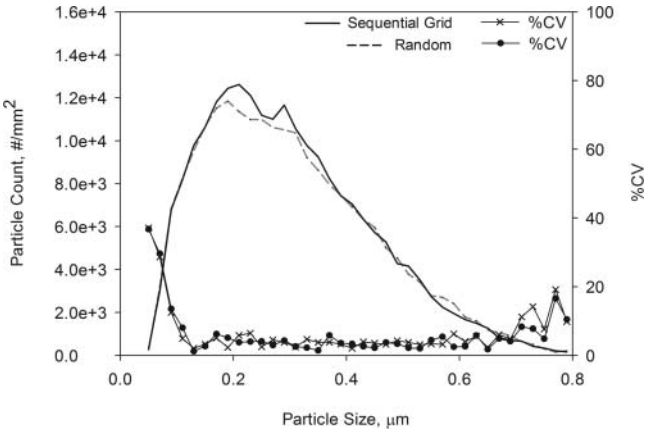


FIG. 6. Size distributions and %CV of the sequential grid and random methods for 49 fields of the same cluster.

between 100 and 650 nm, suggesting that the random method provides an equivalent, representative method for quantifying particles across the MPAS substrate. This result is ideal, as the sequential grid method is very time consuming to set up, and has a built-in bias, because the field sites need to be manually programmed. In contrast, very few coordinates need to be established for the random method, and it has a built-in lack of bias quantification approach, especially for cases where numerous fields and a wide spatial area need to be evaluated. Thus, the random method is considered to be better than the sequential method for quantification of samples with both low and high concentrations.

Since highly efficient protective clothing is expected to effectively prevent greater than 95% of particles from penetrating through the fabric pores (Gao et al. 2011), the minimum number of fields required to achieve a reliable and representative size measurement and count by the CCSEM protocol was evaluated. The total number of particles deposited onto the polycarbonate substrate (i.e., exposure diameter = 20 mm) was quantified by computing the average number of particles per field over the accumulation in the number of fields, ranging from 15 to 476 fields. Table 1 presents the numerical change in size as CMD and surface concentration of particles. It is observed that for evaluation of the full MPAS substrate, about 40–50 fields were required to be quantified to achieve virtually no change in the estimated size and number concentration for the full MPAS sampling surface. At this field count, the substrate showed no change in the modal surface concentration, i.e., at 4.9×10^5 particles/MPAS substrate. Also, quantification of additional fields showed no change in the mean CMD and GSD, which were consistent at 0.296 μm and 1.36, respectively. The lower size and number at the count of fewer fields are likely because of the existence of fewer larger particles, which are more prevalent at the center. Thus, more fields needed to be counted to collect a statistically sufficient number of large particles, while the smaller particles may have been more evenly distributed.

TABLE 1
Size distribution of aerosol deposited across a portion of the MPAS substrate with a diameter of 15 mm, as a function of the number of fields counted

Field count[a]	CMD (μm)	GSD	Median[b] (per MPAS)
476	0.297	1.36	4.9×10^5
300	0.297	1.35	5.0×10^5
200	0.296	1.35	5.2×10^5
100	0.296	1.35	5.1×10^5
50	0.296	1.36	4.9×10^5
45	0.293	1.36	4.7×10^5
40	0.294	1.36	4.6×10^5
35	0.292	1.36	4.3×10^5
25	0.289	1.31	4.6×10^5
15	0.290	1.31	4.7×10^5

[a]Number of particles per field.
[b]Concentration of particles for the corresponding CMD.

The minimum counting and time limit required to accurately determine the surface area concentration for both high and low concentration samples was evaluated. The limit was determined by evaluating the difference between the means of the average number of particles per field on a moving average basis. Figure 7 shows when the relative change in the moving average becomes stable for MPAS substrates having field concentrations of 3, 70, or 383 particles per field. The results show that for samples with higher surface concentrations, between 20 and 35 fields should be counted to achieve no less than 5% change in the average field particle concentration. This result is very

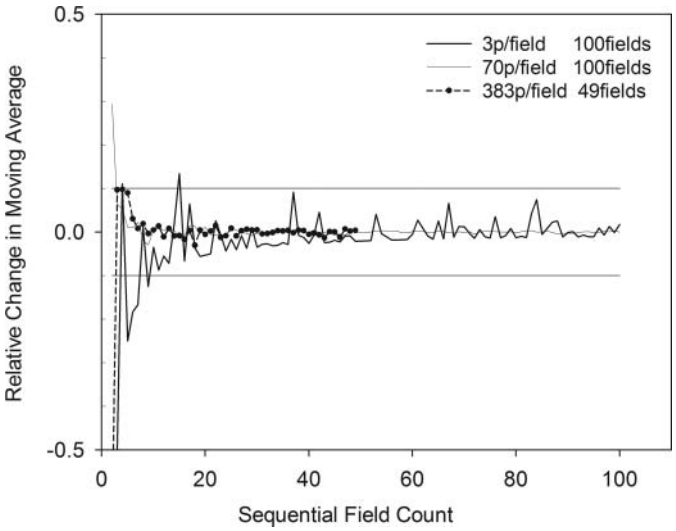


FIG. 7. Relative change in the moving average of particles per field for different particle loadings as a function of the sequence that the fields (0.0023 mm^2 each) were counted by using the random method ($N = 10$): 3 particles per field ($A = 0.23$ mm^2); 70 particles per field ($A = 0.23$ mm^2); and 383 particles per field ($A = 0.88$ mm^2).

similar to the 36 fields required to maintain a consistent average using the random method to evaluate the CCSEM analysis of ambient urban aerosol, as described by Mamane et al. (2001). In contrast, somewhere between 50 and 100 fields are required for counting low concentration samples. The time length of a single scan depends on the number of fields selected, the size of the fields, and the average concentration of particles per field. The size of the field is determined by the level of magnification required for resolving the particles of interest. In this study, a field area of 0.0023 mm^2 and a magnification of 10,000× were used. For the sample parameters used in this study, sampling times varied inversely with the number of particles per field and directly with the number of fields scanned. Figure 7 provides a guide for determining the number of fields required to achieve a variation from the mean difference between subsequent sample means that are less than 10%. For a very low concentration sample of 3 particles per field, 100 fields were quantified, resulting in a scan time of about 15 s per field and 25 min to scan all fields. For a typical high concentration sample of 383 particles per field, the average scan time per field was 65 s, which ran 53 min for the 49 fields that were evaluated. This average varied, requiring less fields for quantification of monodisperse particles within a cluster having about 70 particles per field, which required a count of about 20–25 fields. Evaluation of the full MPAS substrate required about 25–30 fields for areal particle concentrations of about 400 particles per field. The full set of results additionally shows that 77% of all fields measured were within 10% of the moving average and 96% of the fields measured after the 20th field was within the moving average. The results suggest that, on average, regardless of particle loading on the MPAS substrate, consistent results are expected after about 20 fields are quantified for particle number. The analytical time period for 20–30 fields was about 1–2 h, depending on the areal particle concentration.

SUMMARY AND CONCLUSIONS

The following summary and conclusions are made based on this study:

- Particle number across an individual magnet showed a large maximum near the edge of each individual magnet, was somewhat smaller at the center, and was near zero at the corners, likely because of the rapid change in the field gradient between adjacent magnets where a greater induced angular momentum affects smaller particles.
- Particle size across an individual magnet was nonuniformly distributed, favoring smaller particles toward the edge, likely because of the induced angular momentum by the attractive forces of the steep magnetic field gradient between the adjacent magnets of the MPAS.
- Random sampling was evaluated and concluded to be a reliable and better method than the sequential grid method. About 20–30 fields analyzed within 1–2 h, ranging from 2 to 450 particles per field, are sufficient to reliably quantify particle penetration using the MPAS. CCSEM can be used to quantify particle penetration through protective clothing by using the MPAS.

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