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Evaluation of personal aerosol samplers challenged with large particles

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Abstract

The Simplified Test Protocol, developed in our earlier studies for testing personal inhalable aerosol samplers, was evaluated in a specially designed small open-section, close-loop wind tunnel. The sampling efficiencies of three personal inhalable aerosol samplers (IOM, GSP, and Button Aerosol Sampler) were measured with 65 μm particles, using the Simplified Test Protocol at four inlet orientations to the wind (0, 90, 180, and 270°). The results were compared with the data collected from other evaluation approaches. Analysis of variance (ANOVA) has shown that there is no statistically significant difference in the samplers' performance when they are tested in the small and large wind tunnels following the Simplified Test Protocol and in the large wind tunnel following the conventional approach (samplers on a full-size human manikin). Thus, the Simplified Test Protocol has been shown to be suitable for the performance evaluation of personal inhalable aerosol samplers. The new wind tunnel facility was also found useful for handling very large particles, which is a considerable advantage over traditional wind tunnels. Our new wind tunnel was successfully used to measure the sampling efficiencies of the IOM, GSP, and Button Aerosol Sampler when challenged with particles of up to approximately 250 μm aerodynamic diameter at wind velocities of 50 and 100 cm s^{-1}. The data show that the sampling efficiency of the IOM sampler depends significantly on the wind velocity and is above 100% for particles of 165 and 241 μm mass median aerodynamic diameter. This dependence is not statistically significant for the GSP and Button Aerosol Sampler, whose sampling efficiencies are similar to each other and do not change with increasing test particle size at the indicated wind velocities. Also, the sampling efficiencies of the GSP and Button Aerosol Sampler closely follow the independent data obtained by using a breathing and rotating manikin at a wind velocity of 100 cm s^{-1}. The new wind tunnel design is expected to enhance the ability to extend the inhalable convention beyond 100 μm. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Personal aerosol sampler; Large particles; Wind tunnel

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1. Introduction

It has been shown that aerosol particles of different aerodynamic sizes exhibit different aspiration and penetration efficiencies in the human respiratory tract (Lippmann, 1999). Size-selective health-related aerosol size fractions (inhalable, thoracic, and respirable) have, therefore, been defined to semi-empirically describe the fractions of aspirated particles reaching the three major parts of the human pulmonary system: nasopharingal, tracheobronchial, and alveolar (unciliated airways) regions as described by American Conference of Governmental Industrial Hygienists (ACGIH, 2000). These aerosol fractions were experimentally determined by using a breathing human head model (inhalable fraction) and from experiments with human volunteers (thoracic and respirable fractions, Raabe & Stuart, 1999). Several standards, guidelines, and occupational exposure limits have been adopted based on the definition of these fractions (ACGIH, 2000; International Standards Organization, ISO, 1995; European Committee for Standardization, CEN, 1993). These standards establish the inhalable, thoracic, and respirable aerosol conventions as the "target specifications for sampling instruments" when a particular fraction is of interest (ISO, 1995). The inhalable fraction and convention often become the focus of researchers and practitioners because the former defines the amount of hazardous material that may deposit in the entire respiratory tract (Jensen & O'Brien, 1993), while the latter simulates the direction-averaged aspiration efficiency of the human head (Vincent, 1989). The currently used inhalable convention is based on the data obtained in the 1970s and early 1980s and summarized in Soderholm (1989). These data are characterized by a high variability of aspiration efficiency, particularly for large particles. According to the convention, the "inhalability" is about 50% for particles in the 40–100 μm size range and transpired because the highly variable experimental data were averaged. Also, the inhalable convention covers particles up to an aerodynamic diameter of 100 μm. While this diameter is sufficient for most practical situations, it leaves largely unanswered the question of inhalability for particles larger than 100 μm. This question is important for e.g., abrasive blasting, and for other environments where very large particles are normally scarce, because if several of these particles are captured, they may outweigh most other particles collected. Aitken and Donaldson (1996) have suggested "… extending the inhalable convention to particle aerodynamic diameters of at least 300 μm".

One of the goals of the ACGIH/CEN/ISO inhalable convention is to promote the development of aerosol samplers that provide comparable results (CEN, 1999). Several personal samplers capable of extracting the inhalable aerosol fraction (referred to as inhalable aerosol samplers) have been developed over the last 20 years (Vincent, 1989; Kenny et al., 1997; Witschger et al., 1998). The performance requirements set forth in the ISO and CEN standards (ISO, 1995; CEN, 1999) for inhalable samplers have been discussed in our earlier paper (Aizenberg, Grinshpun, Willeke, Smith, & Baron, 2000a), in which adherence to the inhalable convention and low dependence on ambient wind conditions were indicated as the most important criteria for selecting an inhalable aerosol sampler.

A wide variety of the sampler designs translates into significant differences in their performance characteristics. The wind velocity and direction, inlet size, geometry, orientation, aerosol particle size, electrical charge, particle bounce properties, the sampler's conductive properties and other factors affect the samplers' performances in different ways. Over the past several years a number of studies have been published on evaluations and comparisons of the performance characteristics of personal aerosol samplers, including the inhalable ones. In the comprehensive study by Kenny et al. (1997) eight samplers were evaluated: the IOM, seven-hole (both: SKC Inc., Eighty Four, PA), GSP (Ströhlein GmbH & Co., Kaarst, Germany), PAS-6 (produced by the Department of Air Quality, Wageningen Agricultural University, Wageningen, Netherlands), PERSPEC (Lavoro e Ambiente, Bologna, Italy), and CIP10-I (Arelco, Fontenay-Sous-Bois, France), and the 37-mm closed- and open-face cassettes (SKC Inc., Eighty Four, PA). Buchan, Soderholm, and Tillery (1986) compared the performances of the closed- and open-face cassettes. Aitken and Donaldson (1996) compared the IOM and seven-hole samplers. Aizenberg, Grinshpun, Willeke, Smith, and Baron (2000b) evaluated the Button Sampler (SKC Inc., Eighty Four, PA), IOM, GSP, and the 37-mm closed-face cassette.

While these and many other similar studies differ in their experimental setups, they all share one common element: wind tunnels were used for the samplers' evaluation. Because of their versatility and ease of use, wind tunnels are recommended and have become the main tool for evaluating personal aerosol samplers exposed to non-negligible incoming wind velocities (e.g., Lidén, 1994, 2000; CEN, 1999; Ramachandran, Sreenath, & Vincent, 1998). Wind tunnels are also extensively used for particle and airflow studies (e.g., Aizenberg et al., 1998; Wiener, Okazaki, & Willeke, 1988; Sreenath, Ramachandran, & Vincent, 1997; Chung & Dunn-Rankin, 1997) and for testing stationary environmental aerosol samplers such as the PM-10 (Ranade, Woods, Chen, Purdue, & Rehme, 1990).

Our previous publications (Witschger et al., 1998; Aizenberg et al., 2000b) and publications by other researchers (e.g., Ramachandran et al., 1998; Smith, Bartley, & Watkins, 1999; Vincent, 1989) have discussed the limitations that are inherent in wind tunnels used for the applications outlined above. The principal problem is the necessity to place the personal aerosol samplers on a full- or half-size human manikin inside the wind tunnel (Lidén, 1999). This requires a test section having a large cross-sectional area that maintains a low-blockage ratio, which is usually about 10% (Vincent, 1989). This, in turn, results in difficulties in achieving spatial and temporal uniformity of air velocity and particle concentration in the test zone, causing high variability of the sampling efficiency data. Also, the difficulties in handling aerosolized particles (such as injecting, charge neutralizing, mixing, and delivering to the test zone) increase with the particle aerodynamic diameter due to gravitational sedimentation. This effectively imposes an upper limit on the particle size that can be used in conventional wind tunnels. In practice, conventional wind tunnels cannot be used with aerosol particles of about 100 μm and larger. Because of the above, a need was recognized for developing a relatively small wind tunnel facility, which allows evaluating personal aerosol samplers with particles of a broad size range, including those above 100 μm in aerodynamic diameter. Such a facility would allow investigating whether and by how much the accuracy of the inhalable samplers is compromised by collection of very large (>100 μm) particles.

The Simplified Test Protocol (Witschger et al., 1998; Aizenberg et al., 2000b) has been introduced to avoid using large wind tunnels. According to this protocol, the test samplers are mounted on all four rectangular, vertical faces of a three-dimensional Simplified Torso (33 cm wide by 21 cm high by 21 cm deep) that simulates the human upper body, without head, neck, and upper extremities. Instead of rotating a manikin having samplers placed on its front side (traditional approach, used e.g., by Kenny et al., 1997), the sampling is conducted in four directions simultaneously (0, 90, 180, and 270°). It has been shown that this approach results in airflow patterns that are within the range of those created by a full-size manikin (Witschger et al., 1998). Tests in a large wind tunnel have shown that the sampling efficiencies of personal inhalable aerosol samplers mounted on the Simplified Torso versus a full-size manikin are statistically not different from each other (Aizenberg et al., 2000b).

From the beginning, the Simplified Test Protocol was intended for use with a small, simple wind tunnel to fully realize its time- and cost-saving benefits. The present study was originated and carried out as the final step in the lengthy process of validating the Simplified Test Protocol: its feasibility when used in a small wind tunnel was investigated. As part of this effort, we have developed a small wind tunnel capable of handling very large particles (>100 μm).

2. Experimental

2.1. Study objectives

This study had two objectives. The first one was to develop a small wind tunnel capable of handling very large particles (>100 μm) at typical indoor wind velocities ($\leqslant 100$ cm s^{-1}) and to evaluate the new wind tunnel with the Simplified Torso placed in it and following the Simplified Test Protocol. The second objective was to investigate the sampling efficiencies of several personal aerosol samplers when exposed to large particles.

To achieve the first objective, a new wind tunnel was developed (see below) and tested when the Simplified Torso was in it. The testing was performed with particles of 65 μm mass median aerodynamic diameter (MMAD) and 1.44 geometric standard deviation (GSD) at a wind velocity of 50 cm s^{-1}. The resulting data were compared with the data obtained previously in a large wind tunnel when the Simplified Torso and the full-size manikin were alternately placed in it (Aizenberg et al., 2000b). The comparison data were acquired at the same wind velocity using particles of 70 μm MMAD and 1.35 GSD. Since the sampling efficiency curves are rather flat with respect to particle size in this size range [interpolation of e.g., Kenny et al. (1997) data yields 3 and 4% differences in the sampling efficiencies between 65 and 70 μm particles for the IOM and GSP, respectively], it was assumed that the data obtained with these particles having slightly different size distributions could be compared with each other. A three-way analysis of variance (ANOVA) for unbalanced design at the 95% significance level was used for this comparison.

To achieve the second objective, the sampling efficiencies of the test samplers challenged in the small wind tunnel with particles of up to approximately 250 μm were measured at two different wind velocities.

2.2. Experimental variables

Table 1 summarizes the experimental variables of this study. The following personal inhalable aerosol samplers were tested: IOM, GSP, and Button Aerosol Sampler. These three samplers were also investigated in our previous study (Aizenberg et al., 2000b) in which the Simplified Test Protocol was evaluated in a large wind tunnel. All IOM samplers used in this study had stainless steel filter assemblies to reduce moisture absorbance, and, thus, to improve mass stability.

Aluminum oxide particles (alumina, CAS# 1344-28-1, US Filter Surface Preparation Group, Cleveland, OH) were used as test aerosols. Alumina particles are often used in aerosol sampler

Table 1
Experimental variables

Personal aerosol sampler	IOM, GSP, Button
Particle size[a]: MMAD (GSD)	65 μm (1.44); 96 μm (1.36); 165 μm (1.3); 241 μm (1.3)
Wind velocity, U_w (cm s^{-1})	50, 100

[a]MMAD = mass median aerodynamic diameter; GSD = geometric standard deviation

performance studies because they are relatively non-toxic and because their irregular particle shapes are quite similar to those of many important workplace mineral-dust contaminants, such as quartz and coal dust (Mark, Vincent, Gibson, & Witherspoon, 1985). Particles of four different sizes from 65 to 241 μm were used in this study, see Table 1. The particles are characterized by their MMAD and GSD. The particle sizes ranged from the upper half of the established inhalable fraction (ACGIH, 2000) to more than twice its upper size boundary. The large test particle sizes were chosen to investigate the large-particle handling capabilities of the newly developed wind tunnel. The mass distributions of the three largest particle sizes (96, 165, and 241 μm) were obtained in a specially constructed sedimentation chamber at the National Institute for Occupational Safety and Health (NIOSH), Cincinnati, OH. All three mass distributions obtained experimentally were fitted by a lognormal distribution from which the MMADs and GSDs were calculated (Table 1). The mass distribution of the smallest particle size (65 μm) was obtained using the Electrozone (Elzone) technique (Micromeritics Instrument Corp., Norcross, GA). This method was used because it was difficult to accurately determine the mass distribution of the smallest particle size in the sedimentation chamber.

Tests were performed at two wind velocities (U_w), see Table 1. Depending on the combination of the particle aerodynamic diameter, d_a, and the wind velocity, the two U_w's in Table 1 represent the cases of either high-velocity ($V_s/U_w \ll 1$) or low-velocity ($V_s/U_w \sim 1$) flows, where V_s is the particle sedimentation velocity (Grinshpun, Lipatov, & Sutugin, 1990). For example, $d_a = 65$ μm ($V_s = 12.2$ cm s^{-1}) and $U_w = 100$ cm s^{-1} corresponds to the high-velocity regime, while $d_a = 165$ μm ($V_s = 82.2$ cm s^{-1}) and $U_w = 100$ cm s^{-1} is representative of the low-velocity regime. It was important to differentiate between these two flow regimes because of the effect of the V_s/U_w ratio on sampling efficiency (Grinshpun et al., 1990; Grinshpun, Willeke, & Kalatoor, 1993). This effect is especially pronounced for large particles. Also, the tested wind velocities of 50 and 100 cm s^{-1} are typical of indoor occupational environments (Baldwin & Maynard, 1998).

Three repeats of each combination of the experimental variables were performed. Overall, 48 experiments were conducted.

2.3. Experimental setup

Fig. 1 schematically shows the personal aerosol sampler evaluation facility designed and used in this study to test the samplers' performance with large aerosol particles. This facility was a closed-loop open-cross-section wind tunnel. A 5 hp electric motor, located in a weatherproof housing, rotated a tube-axial fan (The New York Blower Co., Chicago, IL), which moved air through a push

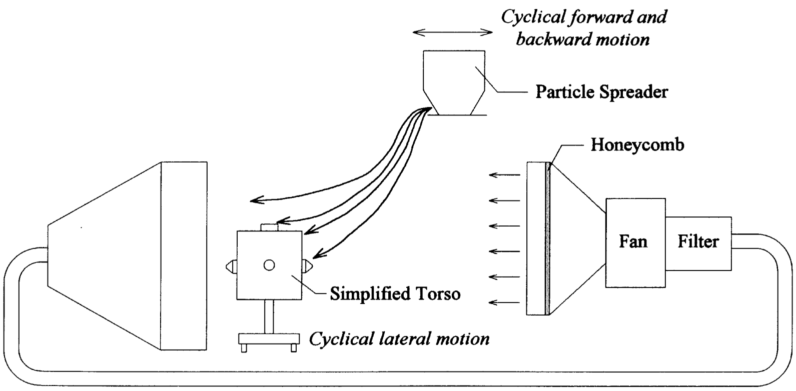

Fig. 1. Experimental setup (side view).

plenum having a 42 cm wide by 61 cm high opening. The cross-sectioned area of the push plenum was approximately 9 times smaller than that of the NIOSH wind tunnel used in the previous stage of the validation of the Simplified Test Protocol (Witschger et al., 1998). The velocity of the ejected airflow could be adjusted by moving the control lever that changed the angle of attack of vanes located inside the fan housing. A 2-cm thick honeycomb with hexagonal cells (3 mm in diagonal) was used to straighten the flow. The working zone was located at a distance of 130 cm from the push plenum. It was encompassed by a supporting frame made of steel that prevented lateral air motion in the vicinity of the working zone and also held various pieces of equipment on its top. This frame was 122 cm wide by 122 cm high by 51 cm deep. These dimensions were sufficient to assure that the support frame does not affect the airflow in the test zone. After passing through the working zone, the air was exhausted into a contracting pull plenum which had the same opening width and height as the supporting frame. The exit cross-section of the pull plenum was circular having a diameter of 6 in (15.24 cm). Upon passing through the pull plenum, the air was cycled through an aluminum air duct of 6 in diameter and a filter bank consisting of a HEPA filter and a pre-filter (American Air Filter, Inc., Louisville, KY). After passing through the filters, the clean air was routed back to the fan. This configuration resulted in turbulence scales of 7 and 11 cm at a distance of 50 cm downstream from the push plenum at 50 and 100 cm s^{-1} wind velocities, respectively.

The aerosols were dispersed using a variable-output spinning-tray particle spreader (model VHD 125, Vigoro Canada Inc., Tillsonburg, ONT, Canada) located 80 cm above and upstream of the test zone. To test for particle aggregation during aerosolization, generated particles were collected on 37-mm PVC filters. Observations under an optical microscope showed no particle aggregates over the entire filter area. The large size and very angular shape of the particles may explain the absence of agglomeration. The spreader was powered by an 115 V DC electric motor that rotated the spinning tray of the spreader at a constant rate of about 180 RPM. The RPM could be adjusted by varying the input voltage supplied to the electric motor. This allowed creation of a sedimentating particle cloud having a typical cross-section of approximately 15 cm wide (parallel to the wind) by 10 cm deep (perpendicular to the wind). Since the width and depth of this cloud were smaller than those of the Simplified Torso, the particle cloud and the Simplified Torso were cyclically moved relative to each other in the axial and lateral directions. This was achieved by the means of two cyclical mechanisms. They were powered by 115 V DC electric motors with built-in 14 : 1 gear reducers, resulting in rotating speeds of 360 RPM. The first mechanism moved the torso (placed on a wheeled carriage) a distance of 24 cm to the left and right from the starting position in the center of the test zone, i.e., a total lateral distance of 48 cm, see Fig. 1. Because the output shaft of the electric motor rotated at 360 RPM at full voltage, a 92 : 1 parallel shaft speed reducer (Dayton Electric Manufacturing Co., Niles, IL) was installed to lower the RPMs. Fine tuning of the speed with which the simplified torso moved laterally was achieved by varying the input voltage to the electric motor. During all experiments the simplified torso moved laterally at 3 cycles min^{-1}, corresponding to a linear velocity of 2.4 cm s^{-1}. The second cyclical mechanism moved the particle spreader forward and backward by 14 cm from its starting position, which was located approximately between 70 and 150 cm upstream of the Simplified Torso. The starting position was determined for each combination of the particle size and wind velocity based on the particles' gravitational sedimentation velocities. The particle spreader moved at 0.5 cycles min^{-1} (0.23 cm s^{-1}). To achieve such a slow movement rate, an additional RPM reducing assembly was installed after the speed reducer and DC motor that were identical to those utilized in the torso cyclical mechanism. This RPM reducing assembly consisted of two gears with a gear ratio of 6 : 1, connected by a chain. The fine adjustment of the speed with which the particle spreader moves axially was achieved by varying the input voltage to the electric motor.

It is generally very difficult and, perhaps, not realistic to achieve homogeneous aerosol distribution of large particles (Lidén & Kenny, 1994). The utilization of the cyclical mechanisms resulted in an arrangement when all samplers were exposed to the particle cloud for the equal time during each

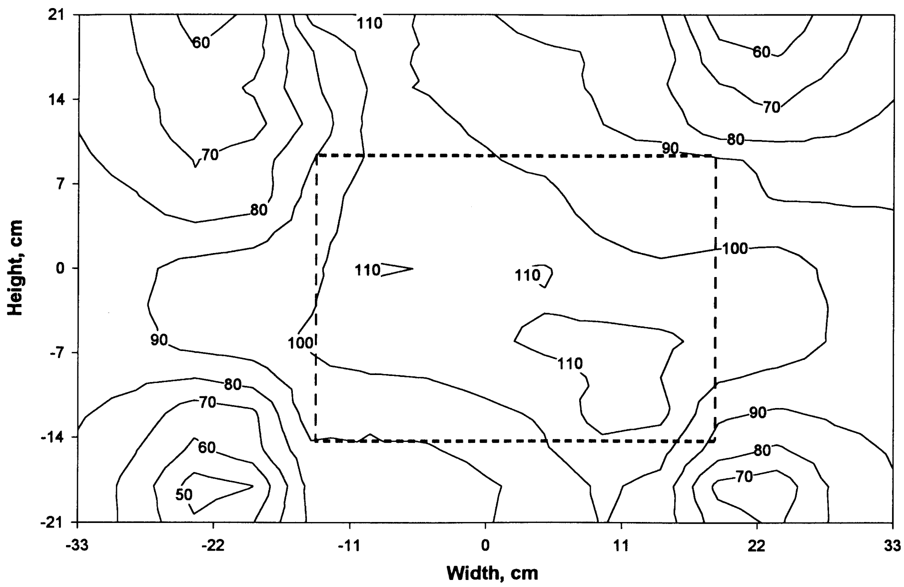

Fig. 2. Air velocity contours (in cm s^{-1}) in the test section (without the Simplified Torso in place) at an average wind velocity of 100 cm s^{-1}.

experiment. Thus, while the temporal and spatial uniformity of particle concentration in the traditional sense was not achieved, all samplers were exposed to the same average concentration for the duration of each experiment.

Fig. 2 presents the air velocity contours (in cm s^{-1}) in the test zone at an average wind velocity of 100 cm s^{-1}, with the Simplified Torso removed from the wind tunnel. The coordinates are shown relative to the center of the region in which the measurements were conducted. The air velocity was measured by a thermal anemometer (model 8384, TSI Inc., St. Paul, MN) that had an accuracy of ± 1 ft min^{-1} (2 cm s^{-1}). The U_w was measured at the nodes of a grid 66 cm wide by 42 cm high (4 times the area of the simplified torso's largest face). Each node was located at a distance of 6 cm from the nearest node. The vertical and lateral components of U_w were found to be negligible (less than 3% of the total U_w). Thus, the air velocity contours shown in Fig. 2 depict the air velocity component parallel to the wind tunnel axis. As seen, there was an area of 34 cm wide by 24 cm high (exceeding in size the largest face of the Simplified Torso) where U_w was within 10% of its nominal value of 100 cm s^{-1}. This area is shown as a dashed rectangle and is slightly off center from the measurement region (Fig. 2). The center of this area was located at a height of 65 cm above the floor. The Simplified Torso was placed in the test zone in such a way, that its center coincided with the center of this 34-cm by 24-cm area. A similar distribution of the air velocity was found at the same location when the wind velocity was changed to 50 cm s^{-1}.

2.4. Collection, handling, and analysis of samples

Fig. 3 shows the top view of the Simplified Torso with the test samplers mounted on it in the following way: Two samplers were placed on each of the two bigger faces of the Simplified Torso (i.e., at 0 and 180° to the wind), while only one sampler was mounted on each of its smaller faces (at 90 and 270° degrees to the wind). Thus, a total of six samplers, consisting of at least two different types, were involved in each experiment, see Fig. 3. This approach has been recently validated (Aizenberg et al., 2000b). Each sampler was connected to a personal air pump (model 224-PCXR8, SKC Inc., Eighty Four, PA). These pumps created flow rates through the samplers' inlets as follows: IOM: 2 l min^{-1}; GSP: 3.5 l min^{-1}; Button Aerosol Sampler: 4 l min^{-1}. These were the nominal flow rates recommended by the samplers' respective manufacturers. The pumps were calibrated using a soap-bubble calibrator (model M-5, A.P. Buck Inc., Orlando, FL). The

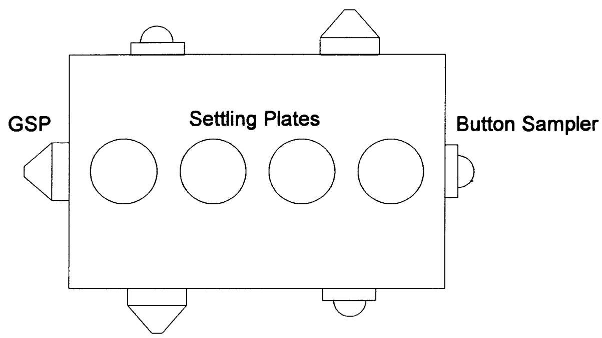

Fig. 3. Simplified Torso with test personal aerosol samplers and settling plates mounted on it (top view).

calibration of the pumps was checked before, during, and after each experiment using rotameters built into each pump.

The bottom parts of four two-piece 37-mm cassettes with filters inside served as sedimentation collection plates and were placed on top of the Simplified Torso along its longitudinal axis, as shown in Fig. 3. These were used for measuring the reference ambient concentrations. More details on this approach are given in the next two subsections.

Due to the high output of the particle spreader, the duration of each experiment was 14 min. The particulate masses collected on the filters during this time were sufficient for gravimetric analyses. No filter overloading occurred.

Type A/E Glass-Fiber filters (GFF, Pall Gelman Sciences Corp., Ann Arbor, MI) were used with all test samplers and sedimentation plates. These filters are recommended for the gravimetric analysis (SKC, 2000). Filters of 37-mm diameters were used with the GSP and the 37-mm cassettes (used for passive collection). Filters of 25-mm diameters were used with the IOM and the Button Sampler. The filters (of the Button Sampler and 37-mm cassettes) and filter assemblies (of the IOM and GSP samplers) were pre- and post-weighted, using an analytical balance that had an accuracy of ± 100 μg (Model AE 200, Mettler–Toledo Inc., Columbus, OH). This accuracy was sufficient because the typical filter loading was of the order of 20–50 mg. Prior to each weighing, the filters and filter assemblies were environmentally equilibrated in a dessicator in which constant relative humidity (15 ± 5%) and temperature (24 ± 1°C) were maintained.

2.5. Sampling efficiency and measurement of the reference concentration

The direction-specific aerosol sampling efficiencies of all samplers were calculated according to the following formula:

$$E_S = \frac{C_{SAMPLER}}{C_{REFERENCE}} 100\%, \tag{1}$$

where $C_{SAMPLER}$ is the measured aerosol concentration, mg m^{-3}, and $C_{REFERENCE}$ is the reference ambient concentration, mg m^{-3}.

The direction-averaged sampling efficiencies were calculated according to the following self-explanatory scheme:

$$E_{\text{dir-}avg} = \tfrac{1}{4} \times (E_0 + 2E_{90} + E_{180}), \tag{2}$$

where E_0, E_{90}, and E_{180} are the sampling efficiencies measured at 0, 90, and 180° to the wind, respectively.

Traditionally, the reference concentration in wind tunnels is measured using isokinetic aerosol samplers. However, as indicated above, the mathematical models describing the particle aspiration efficiency into isokinetic probes depend on the flow regime (i.e., on the sedimentation to the wind velocities ratio, V_s/U_w). Grinshpun et al. (1990) have shown that the inertial aspiration efficiency for a thin-walled sampler (as in isokinetic samplers) depends on both this ratio and the particles' Stokes number (*St*) for low-velocity flow. In contrast, for high-velocity flow, the aspiration efficiency is affected mostly by the *St*. These relationships were generally derived semi-empirically and have not been validated experimentally with the large particles used in the present study. Thus, we did not use the isokinetic sampler approach in our tests.

Instead, passive particle collection was used to determine the reference concentrations. Four bottom parts of two-piece 37-mm filter cassettes were placed on top of the Simplified Torso, see Figs. 1 and 3. Each bottom part had a 37-mm filter inserted in it, which was used as a settling collection plate, as described above. Although any container open at the top and capable of holding a 37-mm filter could have been used, the bottom parts of the 37-mm cassettes were chosen because they were readily available and because the filters fitted tightly inside them. The typical filter loading on these "sedimentation plates" was about 125 mg.

To obtain the reference aerosol concentration, sedimentation velocities of the particles used have to be known. However, because the sedimentation velocity is a non-linear function of the particle aerodynamic diameter ($V_s \sim d_a^2$), use of the V_s, calculated for a distribution's MMAD as a single characteristic sedimentation velocity, would not yield accurate results and, thus, is not appropriate. Alternatively, a numerical integration was used to convert the net collected particulate mass, M, to aerosol mass concentration. First, lognormal mass distributions known for each particle size were converted to normal distributions using a logarithmic transformation. Next, from each of these normalized distributions, a distribution average, standard deviation, and, therefore, parametric best estimates of distribution percentiles were calculated using the unit normal distribution (Berthouex & Brown, 1994). The percentiles thus obtained were: 0.02; 5–95% in the increments of 5; 96; 98; and 99.98% (total of 23). The last 5% of the distribution required more densely packed points because the particle diameters in the tail of the underlying distribution increased rapidly. The aerodynamic diameters corresponding to each of the above percentiles could be calculated as their antilogs. Thus, the whole lognormal distribution was subdivided into 22 segments. Each segment had known upper and lower boundaries, d_a^p and d_a^{p+1}, and a known fraction of the total collected mass, M. The concentration, c_p, created by the particles within each distribution segment was calculated as follows:

$$c_p = \frac{m_p}{\mathrm{A} \times 840 \times V_s^p \times 10^{-6}}, \tag{3}$$

where $m_p = M$ (percentile^{p+1} − percentile^p) is the fraction of total collected mass contained within the segment, mg; A is the area of the 37 mm filter (10.75 cm^2); 840 is the duration of each experiment in seconds (14 min = 840 s); 10^{-6} is the conversion factor; and

$$V_s^p = 0.003\left(\frac{d_a^p + d_a^{p+1}}{2}\right)^2 \tag{4}$$

is the settling velocity of particles having a diameter equal to the middle of the segment, cm s^{-1}.

The reference concentration was then calculated as the sum of all concentrations yielded by (3):

$$C_{\mathrm{REFERENCE}} = \sum_{i=1}^{23} c_p^i. \tag{5}$$

To expedite these calculations, a program in C++ was written. Coefficients of variation (CV) of the reference concentration within each experiment exceeded 12% only three times, having a typical CV value of about 5%.

3. Results and discussion

3.1. Comparison of the sampling efficiencies in the small versus large wind tunnels

A three-way ANOVA was used to compare the sampling efficiencies of the IOM, GSP, and the Button Sampler at $U_w = 50$ cm s^{-1} in three different situations: the samplers were mounted on the Simplified Torso in the small wind tunnel ($d_a = 65$ μm) and on the Simplified Torso and full-size manikin in the large wind tunnel ($d_a = 70$ μm), as described above. As intuitively expected, sampler type, and orientation to the wind, and their interaction were found to be highly statistically significant (p-value = 0.0001). However, the mounting of the samplers (i.e., the body and wind tunnel size) did not significantly affect the sampling efficiencies of the three samplers (p-value = 0.103). To support the conclusion of the ANOVA, Student–Newman–Keuls (SNK) multiple comparison tests of the samplers' mean sampling efficiencies were performed. This analysis found no significant difference between the means at the 95% significance level. The results of both the ANOVA and SNK procedures supported each other and allowed us to conclude that the sampling efficiencies of the three personal inhalable samplers tested were not significantly different when the samples were tested in accordance with the Simplified Test Protocol versus the conventional full-size manikin/large cross-sectional wind tunnel technique.

3.2. Sampling efficiencies of the test samplers challenged with large particles

Fig. 4 presents the direction-averaged sampling efficiencies of the IOM, GSP, and Button Sampler challenged with particles of four different sizes (see Table 1) and measured at two wind velocities: $U_w = 50$ cm s^{-1} (A) and 100 cm s^{-1} (B).

The dashed curve in Fig. 4B represents the sampling efficiency of a rotating manikin breathing at 20 l min^{-1}, reported by Aitken and Donaldson (1996). Fig. 4A does not have the corresponding curve since $U_w = 50$ cm s^{-1} was not involved in the Aitken and Donaldson's study. Likewise, the Button and GSP samplers were not tested by Aitken and Donaldson. Thus, no independent comparison data for these samplers are available. The solid curves in both parts of Fig. 4 represent the established inhalable sampling convention that abruptly ends at 100 μm (marked by the dashed vertical line) at which point a sampling efficiency of 50% is prescribed (ACGIH, 2000).

Fig. 4B show that the IOM's sampling efficiency at $U_w = 100$ cm s^{-1} matches the inhalable convention well at a particle size of 65 μm. However, it noticeably increases for the very large particles. This increase can be explained by the effect of wind on the performance of the IOM sampler: The particles are blown into the sampler through its large open inlet (1.5 cm in diameter). The higher the wind velocity, the more particulate mass will be blown into the sampler. This effect is especially important for the large and very large particles on which the sampler's suction has only a limited effect because these particles have high sedimentation velocities and, thus, do not stay in the vicinity of the inlet long enough to be captured. At $U_w = 50$ cm s^{-1}, the direction-averaged sampling efficiency of the IOM sampler also increases for particle sizes near the upper boundary of the inhalable fraction and beyond it. However, this increase is not as pronounced at the wind velocity of 50 cm s^{-1} as it is for 100 cm s^{-1}. The data obtained for the IOM at both wind velocities exhibited trends similar to those found experimentally for blunt samplers and the IOM samplers by Grinshpun et al. (1990) and Aitken and Donaldson (1996), respectively. Thus, Figs. 4A

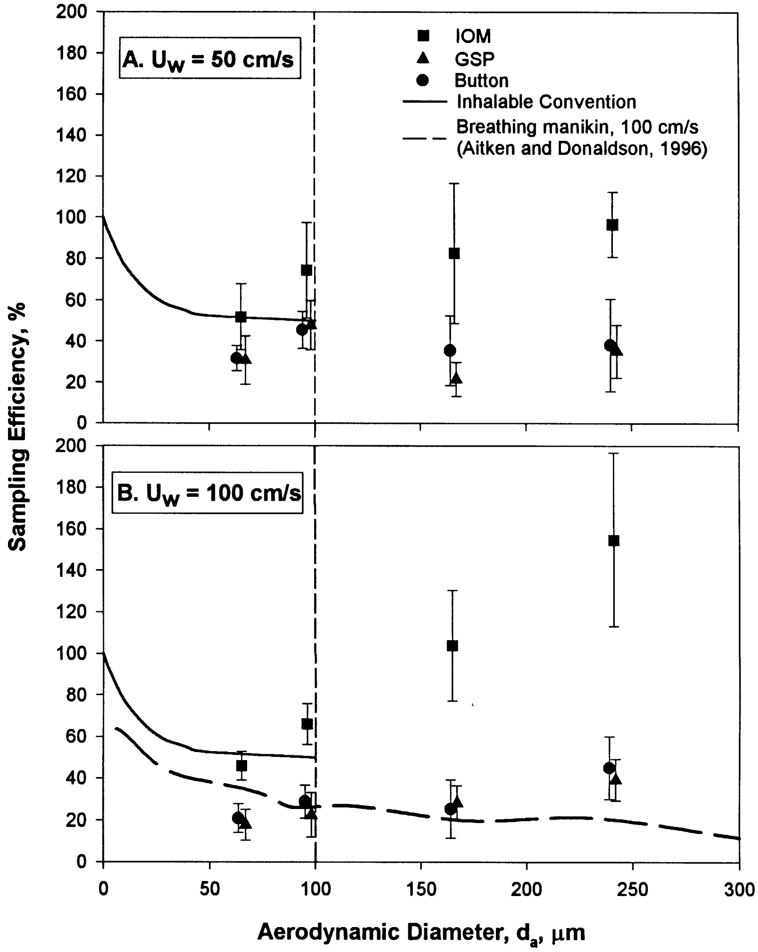

Fig. 4. Sampling efficiencies of the three samplers challenged with very large particles.

and B show that for the IOM sampler exposed to large particles, the mass transfer due to the large-scale air motion dominates the active-air suction.

The sampling efficiencies of the Button Sampler and GSP are below the inhalable convention at $U_w = 100$ cm s^{-1} and close to it at $U_w = 50$ cm s^{-1}. Fig. 4 shows that the sampling efficiencies of the Button Sampler and GSP are similar to each other and below those of the IOM for both wind velocities tested. This trend in a large wind tunnel has previously been noted by Aizenberg et al. (2000a).

The sampling efficiencies of the Button Sampler and the GSP do not essentially change with increasing particle size, (Figs. 4A and B). This can be attributed to differences in geometries between these two sampler inlets and that of the IOM sampler. A long, conical inlet of the GSP sampler terminates in an opening that is several times smaller than that of the IOMs. Thus, fewer particles can be blown into the sampler by the incoming air. The Button Sampler's inlet is protected by a curved screen of 21% porosity with 381 μm orifices. This effectively prevents most of the large particles from entering the inlet regardless of the U_w.

Fig. 4B indicates that the sampling efficiencies of the GSP and the Button Aerosol Sampler are close to the breathing manikin's curve. While more measurements are necessary for a more definitive conclusion, our study shows that these samplers may be useful for investigations of personal exposure to very large particles.

To investigate the effect of wind velocity, the data presented in Figs. 4A and B were compared using paired *t*-tests conducted on the average sampling efficiency values. These tests have shown that the U_w does not significantly affect the sampling efficiencies of the Button Sampler and the GSP (the *p*-values were 0.23 and 0.43 for the Button Sampler and the GSP, respectively).

4. Conclusions

When the IOM, GSP, and the Button Aerosol Sampler were mounted on the Simplified Torso in the small wind tunnel and subjected to 65 μm MMAD particles, no statistically significant difference was found between these sampling efficiencies and those obtained in the large wind tunnel on either the full-size manikin or the Simplified Torso.

The tests conducted in the newly developed wind tunnel, according to the Simplified Protocol, show that the sampling efficiency of the IOM sampler significantly increases with aerodynamic particle diameter when tested with very large particles at $U_w = 100$ cm s^{-1}. This effect is less pronounced for $U_w = 50$ cm s^{-1}.

The sampling efficiencies of the GSP and the Button Sampler were not significantly dependent on the wind velocity. Also, their sampling efficiencies did not significantly change with particle size in the very large particle size range, especially at the higher wind velocity of 100 cm s^{-1}. This has been attributed to the inlet geometry of these samplers that impedes the particles' ability to be blown into the inlet by the incoming air. Generally, the sampling efficiencies of the GSP and the Button Sampler follow each other closely and are below those of the IOM sampler. The sampling efficiencies of the GSP and the Button Sampler closely match the sampling efficiency of the breathing manikin.

The small wind tunnel design developed in this study has been shown to adequately handle very large particles for testing personal aerosol samplers.

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