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Design and Use of a Settling Chamber for Sampler Evaluation Under Calm-Air Conditions

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A compact, low cost, and easy to operate experimental system was developed for evaluating personal samplers in a calm-air environment. The system can provide uniformly distributed monodisperse microspheres up to 69.7 μm in a quiescent environment for determining sampler efficiencies using a fluorescence method. The reference concentration was measured using one vertical and two horizontal sharp-edged probes. The vertical sampling probe met the criterion for greater than 90% sampling efficiency for upward facing cylindrical probes given by Agarwal and Liu, except at the particle size of 69.7 μm. In addition, the consistent agreement among all three reference sampling probes at all particle sizes tested implied that representative measurements of aerosol concentrations in the test section were achieved. In this study, the RespiCon (Model No. 8522, TSI Inc., St. Paul, MN, USA) and IOM (Cat. No. 225-70, SKC Inc., Eighty Four, PA, USA) personal aerosol samplers were evaluated in the system with air velocities in the sampling region below 1.5 cm/s. The sampling efficiency of the IOM was near 100% at all particle sizes, while the RespiCon matched the conventional respirable and thoracic convention curves but undersampled the inhalable fraction.

INTRODUCTION

In recent years, conventions have been established for measurement of airborne dust concentrations in the workplace. These conventions have been based on the aspiration efficiency of mouth-breathing manikins tested in wind tunnels over a range of wind speeds from 1.0 to 4.0 m/s. The same conventions describing the size dependent penetration properties of aerosol particles in the human respiratory system have been published by the American Conference of Governmental Industrial Hygienists (1997), the International Organization for Standardization (1983), and the European Committee for Standardization (1992). A recent study by Baldwin and Maynard (1998) found that normal workplace wind velocities are much lower than the 1.0 to 4.0 m/s used in establishing the criteria for measuring dust concentrations in the workplace and in fact rarely exceed 20 cm/s. Although many workplaces have wind speeds below 20 cm/s, movement by the workers will give a higher effective wind velocity relevant for sampling. Nevertheless, there are many situations where the worker is at rest and a low air movement criteria would apply. Aitken et al. (1999) have shown that in low air movement environments the aspiration efficiency (oral breathing) is greater than the current inhalable convention. In a companion paper by Kenny et al. (1999), several personal inhalable samplers were tested in a low air movement environment. It was shown that on average the same results were obtained with and without a manikin present. Sampling efficiencies for the IOM (Mark and Vincent, 1986), GSP (conical inhalable sampler produced by Strohlien Gmbh), and seven-hole (produced by Casella Ltd) samplers measured in this low air movement environment were generally higher than in previous wind tunnel tests at an external wind speed of 0.5 m/s, while 37 mm sampler results were generally lower. These results suggest that more studies should be conducted to provide information on the sampler efficiency, as well as the inhalability curve, in a low air movement environment which is more similar to the conditions in indoor workplaces.

Traditionally, this type of study requires a meter-scale settling chamber with a generation system at the top and samplers to be tested located at the bottom (Marple and Rubow 1983; Chen et al. 1999; Kenny et al. 1999; Koch et al. 1999). However, depending on the requirements of budget, space, operation, and maintenance, it is sometimes not practical to fabricate such a massive system. For instance, this system is not readily transportable. In addition, a system with this huge volume requires the use of a large quantity of generation material to provide a reasonable concentration in the test environment, and thus it is sometimes too costly to provide ideal test aerosols with a desired concentration, especially for monodisperse aerosols with particle sizes >10 μm. Because of this, polydisperse aerosols were normally used in the system and, in turn, the experimental data could not be precisely related to the corresponding particle

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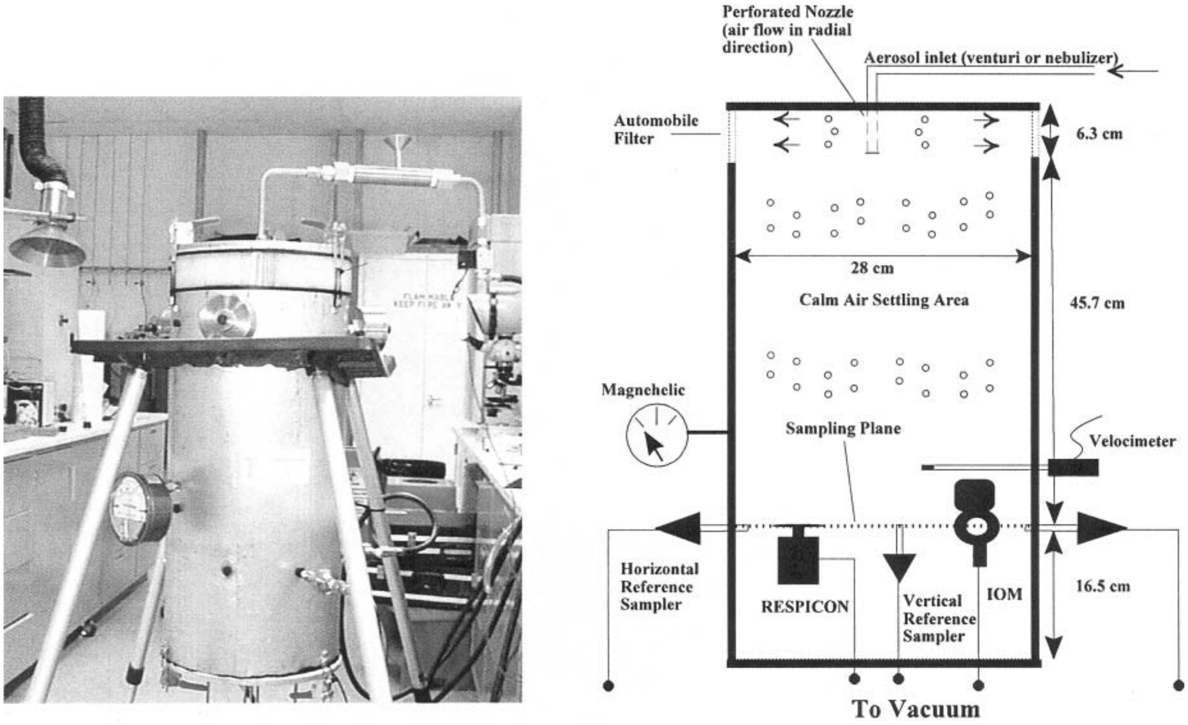
sizes. Therefore, the purpose of this study was to develop a system for testing personal samplers under calm-air conditions (air movement <20 cm/s) with the following characteristics:

1. The system should be low in cost, simple to set up, and easy to operate.
2. The system should be small in size so that monodisperse aerosols can be used for accurate testing.
3. The system should provide uniform aerosol distribution within the sampler test section.
4. The system should have a reliable method for determining the reference concentration.
5. Since Kenny et al. (1999) found similar results with and without a manikin present in the test chamber, valid tests can be performed without a manikin present.

For this study a simple method was developed to produce a homogeneously distributed monodisperse aerosol in a small chamber and sample under calm air conditions. Two samplers were tested in this system, the RespiCon and the IOM. The RespiCon sampler consists of a two-stage virtual impactor and three filters. This sampler gives concentrations of the three health-related dust fractions: the respirable, the thoracic, and the inhalable. The IOM sampler is routinely used to ascertain the inhalable dust fraction. Particles are aspirated into a 15 mm inlet and collected by a two-piece cassette containing a 25 mm filter.

SYSTEM SETUP

The system consists of two aerosol generators, a testing chamber, a dispersion nozzle, an automobile air filter, an electrostatic field meter, a pressure gauge, and three reference probes. A cylindrical, aluminum tube measuring 28.0 cm in diameter and 68.5 cm in length was used as a testing chamber (Figure 1). Aerosol was produced from one of the two generators, depending on the type and size of the test particles. A venturi feeder (Cheng et al. 1989) fabricated by In-Tox Products (Albuquerque, NM) was used for dispersing powders 6 μm and larger, while a medical nebulizer (Hospitak Inc, Cat. No. 952, Farmingdale, NY) was used for producing particles smaller than 6 μm. When the venturi was used, a computer controlled solenoid valve was installed to create pulsating flow in the airstream to help disperse the powders. When the nebulizer was used, a diffusion dryer with desiccant was installed to remove water droplets in the aerosol. After generation, the aerosol entered the chamber through a cylindrical nozzle in the top center of the chamber. The nozzle, 6.3 cm in length, was constructed to contain many symmetrically distributed 1.6 mm holes, which allowed the airflow to enter the



(a) (b)

Figure 1. (a) Photograph of the test chamber and (b) schematic of the test chamber.

chamber traveling in the radial direction. This nozzle was connected to the generator and could be easily rotated manually to reduce the potential bias in the aerosol distribution system due to the generation/dispersion mechanism. An automobile air filter with the same diameter as the test chamber was placed on top of the cylinder to allow airflow to exit the chamber in the radial direction without pressurizing the system, thus creating a quiescent environment in the sampling area (Figure 1b). The aerosol particles, under the influence of both inertia and gravity, were drawn away from the radial flow stream and moved downward into the test section (located 16.5 cm above the end plate) of the chamber. A Magnehelic differential pressure gauge (Dwyer Instrument, Michigan City, MI) was located slightly above the test section of the chamber to ensure that a quiescent atmosphere existed from which the test aerosol would be sampled. Adjacent to the samplers to be tested, three cylindrical sharp-edged probes, two horizontal and one vertical, were used as reference samplers.

Attempts to neutralize the test aerosol using a commercially available Kr-85 bipolar ion source (Model No. 3012, TSI Inc., St. Paul, MN), introduced problems by reaerosolizing particles that were deposited within the Kr-85 source from the previous runs. Since the Kr source was in a sealed container, attempts to remove the deposits within were unsuccessful and the resulting generation of undesirable particle sizes created unacceptable errors. This problem was especially severe when powders larger than 6 μm were used. To avoid this problem, the Kr-85 source was removed from the system. Instead, the chamber was grounded and conductive samplers were used to eliminate electrostatic fields inside the chamber, allowing the aerosol to be introduced without attempting to neutralize it. An electrostatic field meter (Chapman Corp., Model EOS 100, Portland, ME) was used to insure that no accumulated charge was present in the sampling area. Measurements taken in the vicinity of each sampler showed that there was no detectable voltage associated with an accumulated charge (accuracy ±5 volts).

CHAMBER AIR VELOCITY PROFILE

Air velocity profiles were measured to ensure that, even though sufficient air flows were provided to yield adequate mixing at the generation area, calm-air environments were maintained within the sampling area. In the case where a medical nebulizer was used for generating test aerosols smaller than 6 μm, the generation flow rate was relatively small ($<$4.7 l/min) and a calm-air condition can easily be reached by placing an automobile filter at the top of the chamber to allow air movement only within the top portion of the test system. It was, however, uncertain that a calm-air condition could be maintained when the venturi was used for powder dispersion because the generation flow rate could be as high as 80 l/min. For this investigation, a VelociCalc Plus (Model No. 8388, TSI Inc., St. Paul, MN) was used to measure the radial and vertical air velocities within both the generation nozzle area (0–10 cm from the top of the chamber) and the sampling area (16.5 cm for the bottom the chamber). During these measurements, the aerosol generator and all the samplers were operating with the same parameters that were used in the sampler evaluation procedures.

As expected, within the generation nozzle area, the results indicated a pulsating air velocity profile (Figure 2) in the radial direction with an average of 18–20 cm/s. Similar profiles were obtained with an average between 11 and 18 cm/s (Table 1) for the vertical velocities measured at several points lying along a straight line within a plane 10 cm from the top of the chamber. This pulsating phenomenon within the generation area provided the mixing necessary to give a uniform aerosol distribution (results shown later) in the sampling section of the chamber.

The air velocities at the sampling area were measured with both the generation system and the samplers operating, and there was no measurable air movement in the radial or vertical directions. Measurements were made at several locations 5 cm above the sampling plane (readings fluctuated between 0 and 1 cm/s with the detection limit of 1.5 cm/s). In addition, the Magnegelic (with a full scale of ±1 inch H_2O) indicated zero. These results indicate that air velocity within the sampling area fulfills the calm-air criteria ($>$20 cm/s) even when the venturi was operated under a high flow rate (80 l/min).

TEST AEROSOLS AND FLUORESCENCE ANALYSIS

Monodisperse fluorescence-tagged polymer microspheres in either aqueous suspension or powder form (Duke Scientific, Palo Alto, CA) were used in this study. The aerodynamic diameters (D_{ae}) of the particles tested were based on the manufacturer's data and calculated to be 2.0, 6.1, 16.4, 30.7, and 69.7 μm, with σ_g values between 1.05 and 1.15. The green fluorescent dye has maximum excitation and emission at 459 and 512 nm, respectively. During each test run, monodisperse aerosol with a given particle size was dispersed at the top of the chamber, settling into the quiescent portion of the chamber, and then collected by the reference and test samplers near the bottom. After each run, the samplers were dismantled and all filters, probes, and sampler parts were immersed or rinsed with ethyl acetate to remove the fluorescent dye from the particles using the procedure developed by Chen et al. (1999). The fluorescence intensities of the samples were then analyzed using a PTI spectrofluorometer (Photo Technology International, Model C-60, Monmouth Junction, NJ). These data were used to determine relative particle concentrations and consequently to examine the aerosol homogeneity, validate the reference probe concentration, and evaluate the test sampler's efficiency. It is worth mentioning that preliminary tests yielded no background fluorescence on the filters, reference probes, and test samplers.

AEROSOL HOMOGENEITY TEST

Tests were conducted to determine the homogeneity of the particle distribution within the sampling area with no samplers

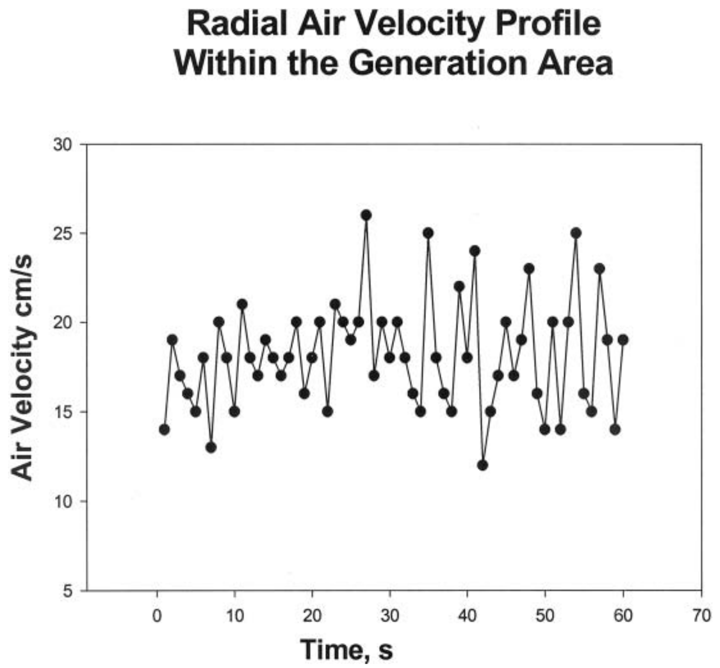


Figure 2. Typical radial air velocity profile with the generation system and samplers in operation. The measurement was taken in the generation area of the chamber at a distance of 10 cm from the center and 2.5 cm from the top of the chamber.

in the chamber. Since larger particles were expected to be more difficult to generate and achieve a homogeneous distribution, the tests were performed using fluorescence-tagged polystyrene latex particles with aerodynamic diameters of 69.7 μm and 30.7 μm. Five 47 mm glass fiber filters were placed flat in the sampling plane (16.5 cm from the bottom) of the chamber (Figure 3). One filter was placed at the center and the other four were placed symmetrically at a distance half way between the center and the chamber wall. These filters were used as passive samplers to collect the sedimenting aerosols. To ensure that any bias in the generation system would be reduced and, therefore, enhancing the homogeneity of aerosol distribution, the generation system (including the dispersion nozzle) was rotated twice during the generation of the aerosol, each with a 120° clockwise rotation (details described below in “Test Sampler Evaluation”). Table 2 shows a typical example of the homogeneity test results in which the fluorescence intensity is measured on each of the filters presented. At both the 69.7 μm and 30.7 μm particle sizes the coefficient of variation was about 3%. These results show that within the sampling section of the chamber our objective of a uniform aerosol distribution has been met with no samplers in the chamber. During the actual sampler test runs, the homogeneity tests were conducted along with the test samplers.

Table 1
Vertical velocities within the generation area of the chamber

Distance from center	Distance from top (cm)	Average velocity (cm/s)
−13.9 cm (near chamber wall)	10	11
−6.9 cm	10	18
0 cm (center of chamber)	10	15
6.9 cm	10	18
13.9 cm (near chamber wall)	10	14

REFERENCE SAMPLING METHOD

A combination of two horizontal and one upward facing sharp-edged probe samplers, each with a 25 mm filter, were used to determine the reference concentration for this system. The same approach was reported by Gibson and Ogden (1977), in which vertical and horizontal sharp-edged probes were compared in a calm-air environment for effectively collecting particles up to 40 μm. Although a pseudo-isokinetic sharp-edged probe was used by Aitken et al. (1999) for measuring the reference concentrations in a larger scale calm-air chamber, it

Table 2
Homogeneity tests for particle sizes 69.7 μm and 30.7 μm

D_{ae} (μm)	Filter 1	Filter 2	Filter 3	Filter 4	Filter 5	CV (%)
30.7	32.4	32.7	30.9	33.3	33.0	2.9
69.7	71.4	69.6	75.3	70.5	72.0	3.0

The fluorescent intensity measurements (arbitrary unit) were compared among the five 47 mm glass-fiber filters.

Figure 3. Photograph of the chamber configuration during homogeneity tests.

was not suitable for the relatively small sized system used in this study.

Table 3 shows the physical parameters of the vertical and horizontal reference probes used in this study and Table 4 shows the fluorescence intensity measurements (described below in "Data Analysis") obtained from these samplers at various particle sizes. Although the results from the vertical probe suggest a possible trend of its collecting more large particles than the horizontal probes (expected because of the particle settling bias), the consistent agreement among the three probes (with

Table 3

Flow parameters of the sharp-edged reference probes and their limiting aerodynamic diameters $D_{L,1}$ and $D_{L,2}$ (μm) based on the (1) Agarwal and Liu (1980) and the (2) Yoshida et al. (1978) criteria

Reference probes	D_i	Q	V_i	$D_{L,1}{}^{*}$	$D_{L,2}{}^{**}$
Horizontal 1	7.7	0.5	18	NA	36
Horizontal 2	7.7	2.8	100	NA	42
Vertical	7.7	3.36	120	45	43

D_i, inlet diameter (mm); Q, sampler flow rate (l/min); V_i, inlet velocity (cm/s); NA, not applicable.

$^{*}D_{L,1}$ was calculated based on $(Stk)(V_s/V_i) < 0.1$, where Stk = inlet Stokes number and V_s = particle settling velocity in cm/s (Agarwal and Liu 1980).

$^{**}D_{L,2}$ was calculated based on $D_i > (99/g)(V_s^{2.43}/V_i^{0.43})$, where $g = 981$ cm/s^2 (Yoshida et al. 1978).

Table 4

Fluorescence intensity measurements obtained from the reference probes at various particle sizes; the intensity is normalized for sampler flow rate

D_{ae} (μm)	Horizontal 1	Horizontal 2	Vertical	CV (%)
2.0	.72	.73	.73	0.9
2.0	.88	.87	.87	0.3
6.1	16.30	17.31	17.94	4.8
6.1	21.40	22.48	23.40	4.5
16.4	2.11	2.03	1.98	3.1
16.4	2.52	2.47	2.48	1.0
30.7	51.13	52.35	53.40	2.2
30.7	67.74	69.55	71.24	2.5
69.7	7.83	8.14	8.44	3.7
69.7	8.78	8.03	8.86	5.4

a coefficient of variation less than 5.4%) seems to imply that the entry efficiencies of the horizontal reference probes match the sampling efficiency of the upward facing reference probe (Gibson and Ogden 1977). However, results of the limiting aerodynamic diameter (D_L), defined as the largest size of the particles which may be collected with an efficiency of $>90\%$ in these probes, seem to indicate that D_L could not be greater than 45 μm (Table 3), based on the Agarwal and Liu (1980) criteria and the Yoshida et al. (1978) formula, and the particles of 69.7 μm could be undersampled by the reference probes when used in the test. Nevertheless, there appears to be consistent agreement in the fluorescence intensity measurements among the three sharp-edged probes, and thus the fluorescence measurements obtained from the three reference probes can be used for estimating the reference concentrations.

TEST SAMPLER EVALUATION

In this study this chamber system was used for evaluating the IOM (Mark and Vincent 1986) and the RespiCon (Koch et al. 1999) personal samplers. For each run, the system was installed with one RespiCon sampler [flow rate = 3.1 l/min], one IOM sampler [2.0 l/min], two horizontal reference probes [0.5 and 2.8 l/min], one vertical reference probe [3.36 l/min], and two 47 mm open-face, glass-fiber filter samplers [no flow] (see layout in Figure 4). In addition, one 37 mm glass-fiber filter (no filter holder) was placed on the top of the RespiCon sampler (not shown in the figure). These three glass-fiber filters were used for passive sampling based on gravitational settling of the particles, and their results were used to confirm aerosol homogeneity during the runs. All samplers and filters were placed at the same height (16.5 cm from the bottom) inside the chamber (Figure 1b).

After checking the flow rates of the samplers with the DryCal flow calibrator (BIOS International, DC-Lite, Butler, NJ), the chamber was sealed, the samplers were activated, and then the test aerosol was introduced into the chamber. For generating powder aerosols (>6 μm), between 50 and 100 mg of the test particles were poured into the venturi funnel over a period of 10–20 s while the flow through the venturi feeder was pulsing under a pressure of 20 psi at a rate of 1 s on and 1 s off. The aerosol was then allowed to settle for 5 min, at which point

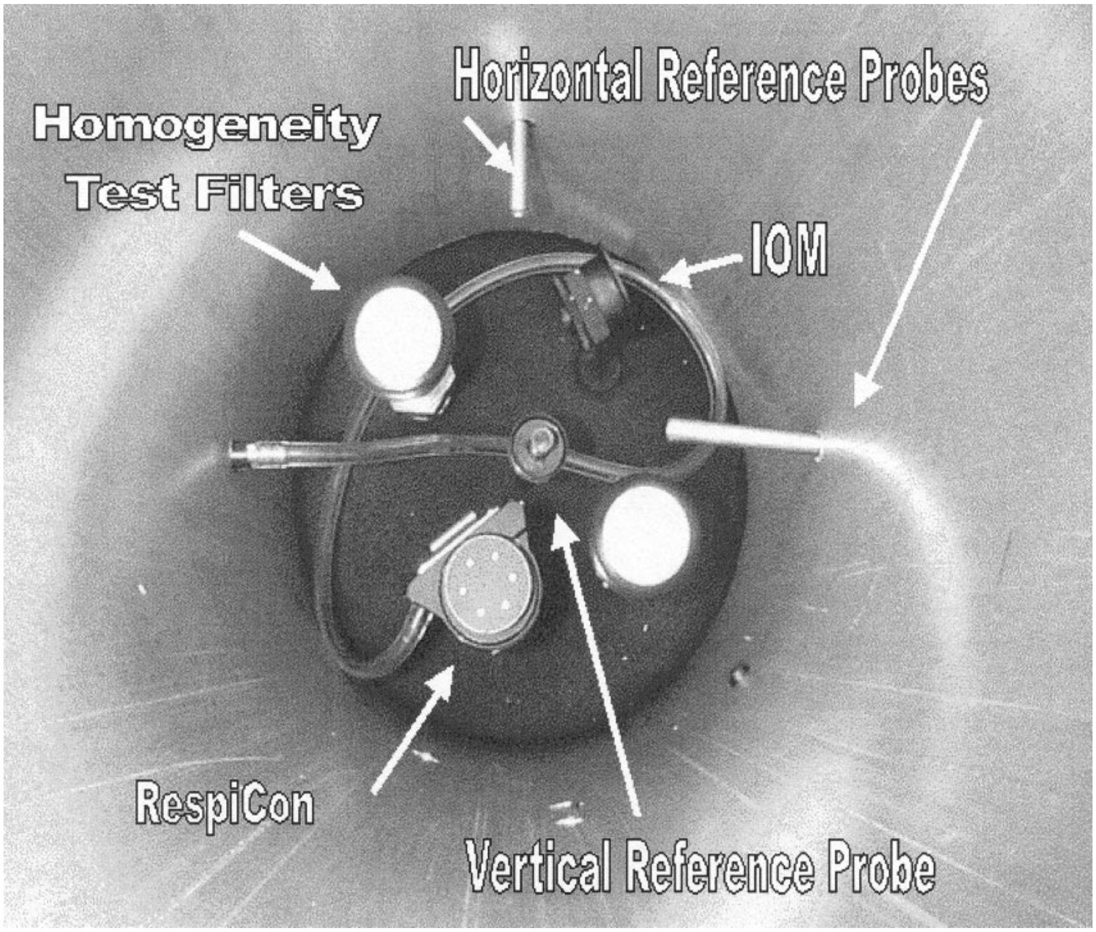


Figure 4. Photograph of the chamber configuration during sampling tests. Note that the 37 mm glass-fiber filter placed on top of the RespiCon is not shown in this photograph.

the aerosol generation system (the venturi and the nozzle) was rotated clockwise 120° and the same steps of adding powder and allowing the aerosol to settle were followed. These steps were repeated one more time through another rotation of 120°. This procedure of rotations was used to ensure that any bias in the generation system would be reduced and, thus, increase the homogeneity of the aerosol distribution. Unlike generating powder aerosols, the procedures were much simpler when a liquid nebulizer was used for generating 2 μm aerosol particles. Liquid suspension was prepared by mixing one drop of the 2 μm concentrated suspension with 18 ml of deionized water. Each run required two liquid refills and about 3 h of sampling time. In addition, the generation system was rotated every 30 min during the sampling. This sampling time was needed to provide sufficient fluorescence for analysis.

At the end of each run, the generation system was turned off first while the samplers were still aspirating (for 5 min) to allow the collection of any aerosol particles remaining in the chamber. After shutting off the samplers, the chamber was opened and the samplers were then removed for fluorescence analysis. The exteriors of the samplers were carefully wiped down with isopropyl alcohol to remove particles adhering to the surfaces. The filters, RespiCon stages, and the IOM cassette were separately either immersed in or rinsed with ethyl acetate to extract the fluorescent dye from the deposited particles. The reference probes were rinsed with ethyl acetate and examined under a fluorescence microscope to ensure that all the particles were removed from the inside of the probes. All liquid samples were then separately drawn through a syringe filter to remove the particles from the ethyl acetate solution to prevent interference with the fluorescence analysis. To ensure that there was no fluorescence loss to the syringe filter, it was rinsed with clean solvent and the filtrate was checked for detectable fluorescence. The fluorescence level in each sample was then determined using the spectrofluorometer. The IOM and the RespiCon were then interchanged and the experiment was repeated to evaluate the level of positional bias in the chamber.

All filters were checked under a fluorescence microscope for possible particle agglomerates. Results showed that the number of agglomerates for all the different particle sizes was $<1\%$, indicating a good dispersion was achieved in the system.

DATA ANALYSIS

In this study the fluorescence intensity measurements were used to indirectly determine the relative particle concentrations and, consequently, to calculate the collection efficiencies of the test samplers. For each run, the relative reference concentration in the chamber was determined by combining together the fluorescence intensity measurements obtained from the filter and the internal surfaces of the reference probe, and then normalized with the flow rate of each probe. For comparison, the reference concentration was determined using either the vertical probe or the average of the two horizontal probes. Similarly, the relative sampling concentrations of the IOM sampler were presented by the fluorescence intensity measurements obtained from the filter cassettes normalized with the sampling flow rates, while the relative concentrations of the three dust fractions (inhalable, thoracic, and respirable) in the RespiCon sampler were obtained from the fluorescence intensity measurements of the three filters normalized with the respective flow rates.

The measured efficiency of a sampler is determined by $C_s/C_r = (FI_s/Q_s)/(FI_r/Q_r)$, where C, FI, and Q represent, respectively, the particle concentration, fluorescence intensity, and flow rate of a test sampler (subscript s) or a reference probe (subscript r). The same formula was used to determine the fractional sampling efficiency for the RespiCon in which the corresponding values of each fraction, rather than the whole test sampler, were used.

RESULTS AND DISCUSSION

Chamber Homogeneity during Test Sampler Evaluations

When tests were being performed with the reference samplers, IOM, and RespiCon aspirating in the chamber, homogeneity tests were conducted with three glass-fiber filters instead of five due to the space requirements of the samplers. Two 47 mm glass-fiber filters were placed halfway between the chamber center and wall at the sampling height (16.5 cm above the bottom of the chamber) and one 37 mm glass-fiber filter was placed on top of the RespiCon sampler (Figure 4). Table 5 shows the fluorescence measured on the filters for each of the sampling runs. Similar to the homogeneity tests performed without the test samplers, the coefficient of variation was small, between 0.8% and 4.6% for all particle sizes tested, indicating that this system provides a uniform distribution within the sampling area during the sampler evaluation.

Table 5

Relative fluorescence intensity measured on glass-fiber filters during sampler test runs; the intensity is normalized for filter area

D_{ae} (μm)	37 mm filter	47 mm filter	47 mm filter	CV (%)
2.0*	ND	ND	ND	NA
2.0*	ND	ND	ND	NA
6.1	4.81	4.78	4.86	0.8
6.1	6.29	6.42	6.32	1.1
16.4	2.92	2.72	2.92	4.0
16.4	3.49	3.26	3.50	4.0
30.7	127.88	138.60	128.16	4.6
30.7	178.07	181.50	172.23	2.6
69.7	133.99	144.90	136.20	4.2
69.7	137.46	135.90	133.80	1.4

*ND, the fluorescence was not detectable; NA, not applicable.

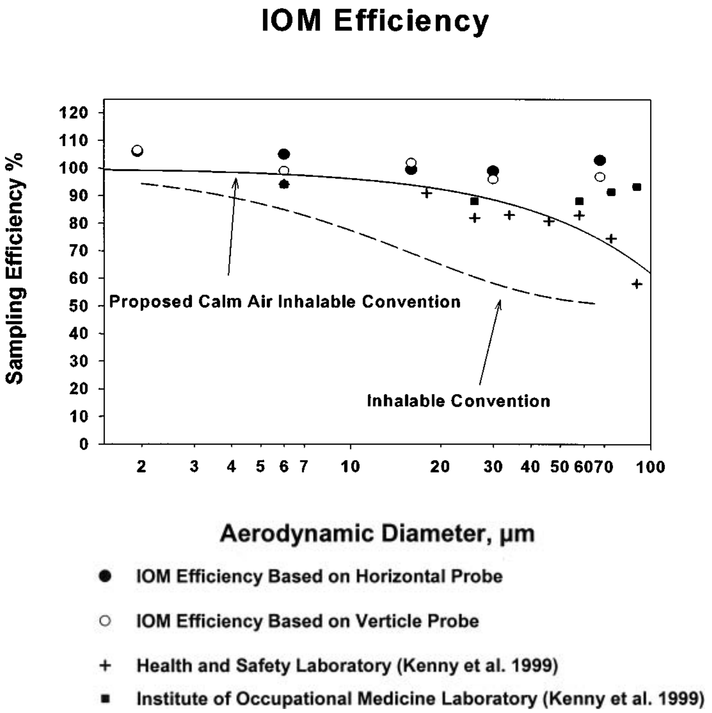


Figure 5. Measured sampling efficiencies of the IOM personal sampler under calm-air conditions.

IOM Sampler

Figure 5 shows the experimentally determined sampling efficiencies of the IOM under calm-air conditions. Each point represents the average of two independent tests in which the positions of the IOM and RespiCon were interchanged to determine the presence of any positional bias. The largest variation, after a change in position, was a 6% difference in sampling efficiency with respect to the vertical reference sampler at a particle size of 16.4 μm with a typical variation of 2–3% with respect to both horizontal and vertical reference samplers. Since no positional bias was detected, the data were averaged. The data indicate that the IOM had a consistent efficiency of close to 100% at all particle sizes tested, performing closer to the revised inhalable convention for low air movement environment suggested by Aitken et al. (1999) but not following the conventional inhalable curve. Compared to Kenny et al. (1999), where pseudo-isokinetic sampling probes were used to determine the reference concentration, our data are very different from those obtained for large particle sizes at the Health and Safety Laboratory (HSL) but similar to those presented by the Institute of Occupational Medicine Laboratory. Although the differences could be due to the nonmonodisperse test particles ($\sigma_g = 1.2$–1.4) used by Kenny et al., the only convincing explanation for this high efficiency at the larger particle sizes in our study is that the 69.7 μm particles may have been undersampled by the reference probes, and thus the efficiency could have been smaller and closer to HSL data. This would be the limitation for a small chamber like ours, in which the reference concentrations for test particles larger than 45 um, based on the Agarwal and Liu (1980) criteria, are likely to be underestimated. Different from the calm-air conditions, the wind tunnel performance tests reported by Li and Lundgren (2000) showed that the IOM oversampled large particles (aerodynamic diameter greater than 20 μm) when the orientation of the inlet was facing the wind and undersampled large particles when the inlet orientation was perpendicular or facing away from the wind. These differences can possibly be explained by variations in inlet sampling efficiencies of the IOM in moving air and nonmoving air environments.

RespiCon Sampler

Figure 6 shows the sampling and classification characteristics of the RespiCon personal sampler under calm-air sampling conditions. Each point represents the average of two independent tests in which the positions of the IOM and RespiCon were interchanged to determine the presence of any positional bias. The largest variation, after a change in position, was a 5% difference in the inhalable sampling efficiency with respect to the vertical reference sampler at a particle size of 16 μm with a typical variation of 2–3% in the inhalable, thoracic, and respirable fractions with respect to both horizontal and vertical reference samplers. Since no positional bias was detected the data were averaged. The size classification data match the respirable and thoracic curves reasonably well for all particle sizes tested; however, they underestimate the inhalable fraction, falling below the

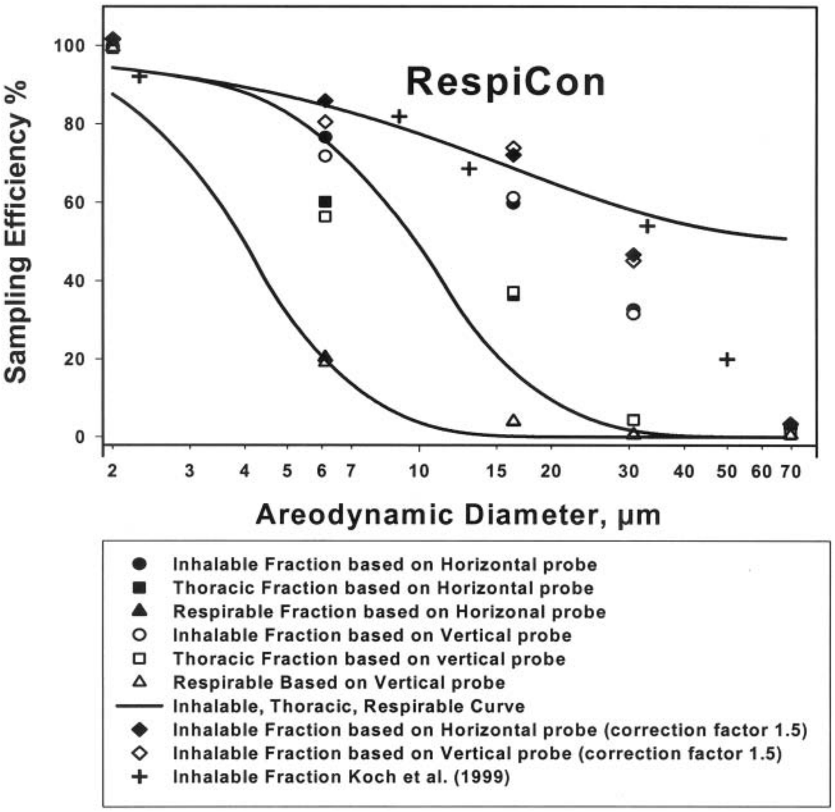


Figure 6. Measured sampling efficiencies of the RespiCon. The data is plotted as measured from the three filter stages and with a correction factor of 1.5 applied to the stage 3 filter mass as originally directed by the manufacturer. Note: TSI, the manufacturer of the RespiCon has sent out an application note recommending users to discontinue applying the 1.5 correction factor originally recommended in the user manual. This change was based on the wind tunnel data of Li and Lundgren (2000).

convention at 6.1 μm and declining to less than 5% sampling efficiency at 69.7 μm. Koch et al. (1999) also tested the RespiCon under calm-air conditions using quasi-monodisperse mineral dust aerosols ($\sigma_g = 1.25$) in a 112 m^3 chamber and found an underestimation of the inhalable fraction for particles >50 μm aerodynamic diameter. Although our sampling efficiency (inhalable fraction) data match well with those of Koch et al. up to about 20 μm, the data of 30.7 μm and 69.7 μm are much lower. One possibility is that our reference probes could have oversampled the 30.7 μm and 69.7 μm particles, resulting in a lower sampling efficiency. However, this seems unlikely because the assumption would have contradicted the undersampling phenomena for particles >45 mm in a calm-air environment (Gibson and Ogden 1977; Yoshida et al. 1978; Agarwal and Liu 1980) and would have made the calculated sampling efficiencies for IOM even higher for large particles. Another possible explanation is that because the test aerosols were not monodisperse (Koch et al. 1999), the fraction of the particles which were smaller than the median size of the distribution but larger than the thoracic fraction could have contributed to the inhalable fraction and resulted in higher collection efficiencies at the designated median sizes. While this study and the calm-air tests performed by Koch et al. showed an underestimate in the inhalable fraction compared to the conventional curve, wind tunnel tests performed by Li and Lundgdren (2000) showed strong agreement between the RespiCon sampling efficiency and the curves for all three size fractions at a wind speed of 0.55 m/s. This suggests that the RespiCon sampler may match the three conventional curves by adopting a correction factor under the calm-air conditions, but it may perform reasonably well (without a correction factor) in a moving-air environment.

CONCLUSION

An experimental system for testing the sampling efficiency of personal aerosol samplers whose intended use is for indoor sampling under calm-air conditions has been developed and utilized to evaluate the IOM and RespiCon samplers. The results of this study show that this system is useful in determining the efficiency of personal aerosol samplers under calm-air conditions and has the advantages of being a low-cost, compact, and transportable apparatus. However, the use of vertical and horizontal sharp-edged probes may limit the maximum aerodynamic diameter of the test aerosol to 45 μm.

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