AUTHORS
Shou-Nan Li[a]
Dale A. Lundgren[b]
David Rovell-Rixx[c]

[a]Industrial Technology Research Institute, Center for Industrial Safety and Health Technology, 11F, Bldg. 51, 195-10 Sec. 4 Chung-Hsing Rd., Chutung, Hsinchu, Taiwan 310;
[b]Department of Environmental Engineering Science, University of Florida, Gainesville, FL 32611;
[c]National Council of the Paper Industry for Air and Stream Improvement, Inc., Southern Regional Center, P.O. Box 141020, Gainesville, FL 32614

This study was supported by the National Council of the Paper Industry for Air and Stream Improvement, Inc. through the Southern Regional Center in Gainesville, Florida.

APPLIED STUDIES

Evaluation of Six Inhalable Aerosol Samplers

Six inhalable aerosol samplers were evaluated experimentally as area samplers using monodisperse solid particles with aerodynamic diameters ranging from 5 to 68 μm. Sampler performance and inside particle loss at two test wind speeds (0.55 and 1.1 m/sec) and three wind orientations (0, 90, and 180°) were investigated. The six inhalable aerosol samplers tested were a RespiCon, an Institute of Occupational Medicine (IOM), a seven-hole, a conical inhalable sampler, a prototype button sampler, and a closed-face 37-mm cassette. The area sampling performance of the RespiCon sampler matched the inhalable convention fairly well. The sampling performances of the other five samplers depended on wind speed, wind direction, and particle size, and they may not be appropriate for area sampling if the wind speeds are greater than 0.5 m/sec.

Keywords: area sampler, inhalable aerosol sampler, personal sampler

Workplace aerosols can cause respiratory system damage, such as nasal cancer and bronchitis, if the aerosols are breathed in and deposit in the human respiratory system.[1] To determine how much aerosol can be breathed in, Vincent and Mark[2] and Armbruster and Breuer[3] conducted wind tunnel tests using a life-size manikin at wind speeds ranging from 0.5 to 4.0 m/sec. They found that inhalation of an airborne particle (i.e., aerosol) decreases with its aerodynamic diameter (D_a). Using their experimental results as a basis, the American Conference of Governmental Industrial Hygienists,[4] the International Organization for Standardization (ISO),[5] and the Comité Européen de Normalisation (CEN)[6] reached an agreement and defined a convention for the inhalability of workplace aerosols:

$$I(D_a) = 0.5[1 + \exp(-0.06D_a)] \tag{1}$$

for $0 \leq D_a \leq 100$ μm, where, $I(D_a)$ = inhalability and D_a = particle aerodynamic diameter (microns). Inhalability for $D_a > 100$ μm is not defined.

Recently, Baldwin and Maynard [7] found that typical workplace wind speeds range from 0.04 to 2.02 m/sec and have an arithmetic mean value of 0.3 m/sec. Therefore, the current inhalable convention, which was based on tests conducted at higher wind speeds (0.5–4.0 m/sec) may not fully reflect human inhalability at lower wind speeds. In low air movement environments (wind speed less than 0.1 m/sec), Aitken et al.[8] found that human inhalability is significantly greater than the current inhalable convention; a revised form of the inhalable convention was suggested.

To quantify the inhalable aerosol concentration accurately, an ideal aerosol sampler should have a sampling performance equal to human inhalability. Workplace aerosol samplers can be used as area or personal samplers. Area samplers are freestanding collection devices, whereas samplers mounted on workers' bodies are called personal samplers. The main advantage of personal sampling is that the aerosol sampled is closer to that to which the worker is exposed.

To evaluate the personal sampling performances of eight different inhalable aerosol samplers, Kenny et al.[9] mounted the samplers on a life-size rotating manikin located inside a testing wind tunnel with the wind speeds ranging from 0.5 to 4.0 m/sec. They found that the personal sampling performances of the eight aerosol samplers fit the inhalable convention fairly well. At low air movement environments, Kenny et al.[10] found that the personal sampling performance of the IOM sampler agreed very well with human inhalability. In addition, they found that the sampling performances of the inhalable aerosol samplers on and off the manikin were equivalent at low air movement environments. This indicates that at wind speeds less than 0.1 m/sec, there was no measurable performance difference between personal and area sampling. However, at a wind speed of 1.0 m/sec, Buchan et al.[11] found that the measured efficiency of personal sampling was significantly greater than that of area sampling for closed-face and open-face 37-mm cassettes. For personal sampling, effects of manikin body on airflow fields and on sampler performance have been shown by many researchers.[12–15] For area sampling, on the other hand, very limited sampler performance data are available for most commercially available samplers, such as a RespiCon, an Institute of Occupational Medicine (IOM), a conical inhalable sampler (CIS), and a seven-hole sampler.

Although personal sampling collects the aerosol samples that better reflect worker exposure, personal sampling requires more labor, instruments, and worker involvement.[16] The requirement of worker involvement in personal sampling makes routine and extensive aerosol monitoring very difficult. In addition, the particles collected on the filter of the personal sampler could be knocked off by body movement of the worker, which would result in a serious sampling error. The other merit of area sampling is that the measured local aerosol concentration can be used for the development of particle control techniques; this would be inconvenient using personal sampling.

Although it is convenient to use area samplers, very few commercially available area samplers have performances that fit the inhalable convention. In low air movement environments, the area sampling performance of the IOM sampler agrees very well with human inhalability.[10] However, at higher wind speeds area sampling performance of the samplers (including IOM) is not fully understood. Therefore, use of personal samplers as area samplers is strongly discouraged by the American Industrial Hygiene Association (AIHA).[17] To evaluate the area sampling performance of samplers at higher wind speeds, this study evaluated six inhalable aerosol samplers experimentally as area (freestanding) samplers using monodisperse, solid particles. Measured efficiencies and inside losses of these six samplers at two wind speeds (0.55 and 1.1 m/sec) and three wind directions (0, 90, and 180°) are discussed. The two wind speeds used represented moderate to high workplace wind speeds. Attempts to test the samplers at a wind speed of 0.3 m/sec were not successful because it was not possible to uniformly mix and horizontally transport particles with D_a greater than ~50 μm in the test chamber at that speed.

MATERIAL AND METHODS

Aerosol Sampler Description

RespiCon Sampler

The RespiCon sampler (Model 8522, TSI Inc., St. Paul, Minn.) shown in Figures 1a and 1b, designed by Koch et al.,[18] has a circular inlet around the inlet-head perimeter. Because of this circular inlet design, aerosol is aspirated into the inlet from all wind directions (360°) at the same time. Therefore, unlike the other samplers discussed in this study, the RespiCon sampler does not have different inlet wind orientations (e.g., 0, 90, and 180°).

Aerosol is aspirated into the RespiCon inlet at a flow rate of 3.10 L/min and then separated into three fractions by two virtual impactors. Inside the RespiCon, as shown in Figure 1b, particles with D_a less than 4 μm are separated in Stage 1 and collected onto the top filter. Particles with D_a greater than 4 μm pass straight through Stage 1 and flow downward to Stage 2. In Stage 2, particles with D_a between 4 and 10 μm are collected onto the filter. Those particles with D_a greater than 10 μm pass straight through the Stage 2 and are collected onto the bottom filter. Particles on these three filters allow the determination of particle concentration for the inhalable, thoracic, and respirable fractions (defined in the AIHA booklet[17]):

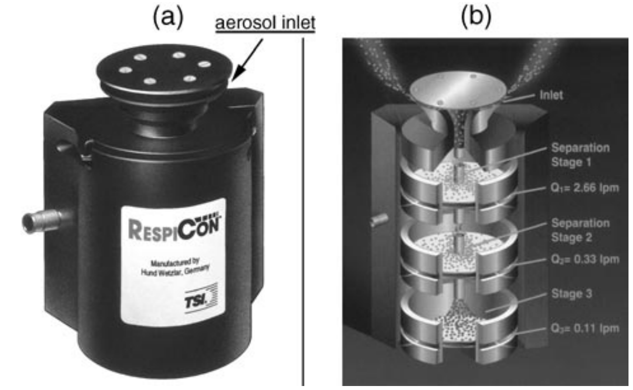


FIGURE 1. (a) Picture and (b) inside schematic drawing of a RespiCon sampler. Source: manufacturer (TSI, Inc.) catalog.

$$C_R = \frac{Mass_1}{Q_1 t} \quad (2)$$

$$C_T = \frac{Mass_1 + Mass_2}{(Q_1 + Q_2)t} \quad (3)$$

$$C_I = \frac{Mass_1 + Mass_2 + Mass_3}{(Q_1 + Q_2 + Q_3)t} \quad (4)$$

where

C_R = particle concentration in the respirable fraction
$Mass_1$ = particle mass on top filter (Stage 1)
Q_1 = sampling flow rate for Stage 1 (= 2.66 L/min)
t = sampling time
C_T = particle concentration in the thoracic fraction
$Mass_2$ = particle mass on middle filter (Stage 2)
Q_2 = sampling flow rate for Stage 2 (= 0.33 L/min)
C_I = particle concentration in the inhalable fraction
$Mass_3$ = particle mass on bottom filter (Stage 3)
Q_3 = sampling flow rate for Stage 3 (= 0.11 L/min)

Particles depositing on the inner surfaces of the RespiCon sampler are considered as inside losses. The RespiCon is the only sampler tested that separates aerosol into the three defined fractions. The other samplers are intended to collect inhalable aerosol.

IOM Sampler

The IOM sampler (Catalog no. 225-70, SKC Inc., Eighty Four, Pa.), shown in Figure 2a, was designed by Mark and Vincent.[19] It has a 15-mm diameter inlet orifice. Aerosol is aspirated into the IOM sampler at a flow rate of 2.0 L/min. Particles aspirated into the inlet are either collected by a 25-mm filter or deposited on the inside surfaces of an internal two-piece cassette. Since particles on both the filter and the cassette are analyzed as the particulate matter sampled, there is no inside particle loss in the IOM sampler.

Seven-Hole Sampler

Aerosol is aspirated into a seven-hole sampler (SKC Inc., Eighty Four, Pa.) through seven 4-mm diameter inlet orifices at a flow rate of 2.0 L/min. Particles collected onto a 25-mm filter are analyzed as the particles sampled, whereas those depositing on the

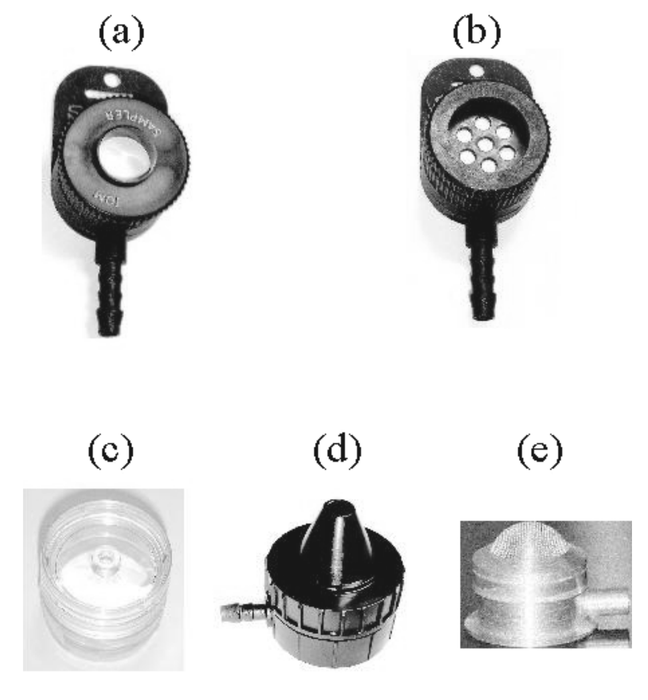


FIGURE 2. Inhalable aerosol samplers used in this study. (a) IOM; (b) seven-hole; (c) closed-face 37-mm cassette; (d) CIS; (e) prototype button.

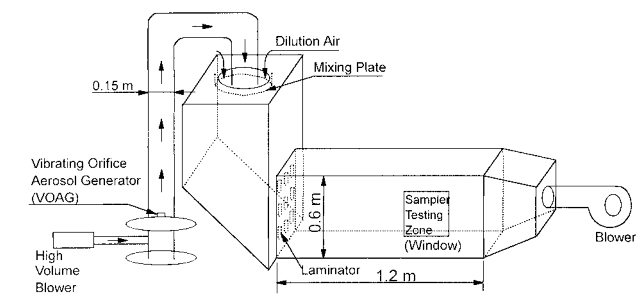


FIGURE 3. Schematic drawing of the sampler testing system

inner surfaces are considered as inside losses. A picture of the seven-hole sampler is shown in Figure 2b.

Closed-Face 37-mm Filter Cassette

Aerosol is aspirated into a closed-face cassette through a 4-mm diameter inlet orifice at a flow rate of 2.0 L/min. Particles collected onto a 37-mm diameter filter (Millipore Inc., Bedford, Mass.) are analyzed as the particle catch, whereas those depositing on the inner surfaces are considered as inside losses. A picture of the closed-face 37-mm filter cassette (Millipore Inc., Bedford, Mass.) is shown in Figure 2c.

CIS

As shown in Figure 2d, the CIS sampler (BGI Inc., Waltham, Mass.) has a conical inlet section. Aerosol is aspirated into the CIS sampler through an 8-mm diameter inlet orifice at a flow rate of 3.5 L/min. Both the particles collected by a 37-mm filter and those depositing on the filter holder are analyzed as the particle sample, whereas those depositing on the conical inlet section are considered as inside losses.

Prototype Button Sampler

The button sampler (SKC Inc., Eighty Four, Pa.) shown in Figure 2e, designed by Kalatoor et al.,[20] has a hemispherical metal-screen inlet. The screen contains many 381-μm diameter openings and has a total open area of 21%. This screen design prevents large noninhalable particles ($\gg$100 μm) from entering the inlet. Aerosols with physical diameters less than the screen diameter are aspirated through the inlet at a flow rate of 2.0 L/min and collected onto a 25-mm diameter filter. In this study, only those particles depositing on the front filter gasket were quantified as inside losses.

Test Methods

Solid, monodisperse, ammonium-fluorescein test particles with D_a ranging from 5 to 68 μm were generated using a vibrating orifice aerosol generator (VOAG) (Model 3050, TSI Inc.) To effectively transport large VOAG generated particles, the drying air supplied to the VOAG was modified as shown in Figure 3. Liquid particles from the VOAG were lifted upward, dried, and directed into a wind tunnel using an airflow rate of 425 L/min. In the vertical wind tunnel section, the test aerosol was mixed with a dilution air using a mixing plate, then transported horizontally to the sampler testing zone. For the 68 μm particles, the mixing plate was removed to reduce the observed high particle losses.

At the beginning of the horizontal wind tunnel section, a perforated plate (called a laminator) with 20 rectangular openings of 25 × 100 mm was used to reduce large-scale turbulence generated at the vertical mixing section and to flatten the highly nonuniform velocity profile due to the 90° bend. In essence, turbulence larger than the laminator opening was eliminated. The remaining small-scale turbulence was desirable for the particle mixing. Two wind speeds (0.55 and 1.1 m/sec), measured using a hot-wire anemometer (Model 8330, TSI Inc.), were used in this study. At these two wind speeds, the airflow was turbulent (Reynolds numbers = 3600 and 7300, respectively). Although the turbulence scale and intensity at the sampler testing zone were not measured, a fairly uniform velocity profile with difference less than 10% was found over an area of about 600 cm² at the central region of the wind tunnel using the hot-wire anemometer. This central region was where the samplers were located for testing.

To assure the uniformity of test particle diameter, during each syringe run of the VOAG, particles were collected at the sampler testing zone using an open-face 37-mm cassette with the sampler inlet air velocity equal to the test section air velocity. The sampling flow rates for the open-face cassette at 0.55 and 1.1 m/sec wind speeds were 35.5 and 71 L/min, respectively. The diameters of the test particles were measured using a light microscope. To determine the doublet and triplet ratios of the VOAG generated particles, for each particle diameter about 500 particles were counted using the light microscope. It was found that doublet percentage was less than 3% and triplet percentage less than 1% for all five test particle diameters (D_a = 5, 10, 21, 41, and 68 μm). Because of the low doublet and triplet ratios, no correction was made to the measured sampling efficiency. The low doublet and triplet ratios could result from the higher drying airflow rate (425 L/min) and larger drying column (150 mm) used in this study, which reduced the coagulation of liquid singlets to form doublets and triplets. Besides, doublets and triplets had higher loss chances (than singlets) during transportation inside the wind tunnel, which would also decrease the doublet and triplet ratios measured at the sampler testing zone.

The VOAG particle mass output was unacceptably low for small particles. Therefore, polydisperse uranine test particles with a mass median aerodynamic diameter (MMAD) of 1.6 μm and a geometric standard deviation (GSD) of 2.7 were generated using a Collison atomizer. The MMAD and GSD values were measured at the sampler testing zone using a Marple Personal Cascade impactor (without a visor) (model 298, Anderson Samplers, Inc., Atlanta, Ga.). The MMAD and GSD values were determined by plotting the cumulative particle weight gains versus the published cut-point diameters[21] of the impactor stages on a log-probability paper. Particle losses inside the Marple impactor were not recovered for determining the MMAD and GSD values.

For each test condition, three sampling positions with particle concentration difference less than 10% were located in the sampler testing zone by simultaneous measurement using three isokinetic sharp-edge probes (Andersen Instruments, Inc.). Two or three continuous tests using three isokinetic probes were conducted to measure the temporal particle concentration variation at these three sampling locations, which were found to be less than 10%. After locating these three positions, in each test, one isokinetic probe and two inhalable aerosol samplers were simultaneously put at the same positions as those located by the three isokinetic probes and then the samplers' positions were sequentially changed. The measured efficiency and the inside loss of the inhalable aerosol sampler were determined using Equations 5 and 6, respectively:

$$\text{Measured Efficiency} = \frac{C_{inh}}{C_{isok}} = \frac{\text{Mass}_{inh}/Q_{inh}}{\text{Mass}_{isok}/Q_{isok}} \tag{5}$$

$$\text{Inside Loss} = \frac{\text{Mass}_{loss}/Q_{inh}}{\text{Mass}_{isok}/Q_{isok}} \tag{6}$$

where

C_{inh} = particle concentration measured by the inhalable aerosol sampler
C_{isok} = particle concentration measured by the isokinetic probe
Mass_{inh} = mass of particle sample collected by the inhalable aerosol sampler
Mass_{isok} = mass of particles collected by the isokinetic probe
Mass_{loss} = mass of particles depositing on the inner surfaces of the inhalable aerosol sampler
Q_{inh} = airflow rate through the inhalable aerosol sampler
Q_{isok} = airflow rate through the isokinetic probe

Particles collected by the filters and those depositing on the inner surfaces of the samplers were dissolved in a 0.1 N sodium hydroxide (NaOH) solution and then quantified using a fluorometer (Model 112, Turner Assoc., Palo Alto, Ca.). The fluorometer was calibrated using the NaOH diluted aliquots of known particle concentration. To recover the particle losses inside the inhalable samplers and the isokinetic probes, different procedures were used. For example, to recover the inside losses on the inlet head of the RespiCon sampler, the outside surfaces of the inlet head were first cleaned using a NaOH-soaked cotton swab. Particles depositing inside various sampler sections were then dissolved and washed out using a 0.1 normal NaOH solution. Particle losses inside the seven-hole sampler were recovered using a NaOH-soaked cotton swab, and then the swab was sonicated 5 minutes in an NaOH solution. Particle losses inside the CIS conical inlet and the closed-face 37-mm cassette were recovered by carefully rinsing the inside surfaces using a NaOH-containing squeeze bottle. Before rinsing the inside surfaces, the outside surfaces around the inlets were carefully cleaned to prevent the particles on the outside surfaces from being included.

The airflow rate through each sampler (including the isokinetic probe) was monitored using a rotameter and controlled by a critical orifice. The rotameters and the orifices were calibrated using a calibrated Gilibrator (an electronic bubble meter) (Gilian Instrument Corp., Wayne, N.J.). To minimize the effect of filter pressure drop on flow rate variation, glass fiber filters (A/E type) were used for particle collection in all samples. The glass fiber filter used had a collection efficiency greater than 99.9% for all test particles used in this study. The sampling flow rate difference due to filter loading was found to be less than 1%.

RESULTS

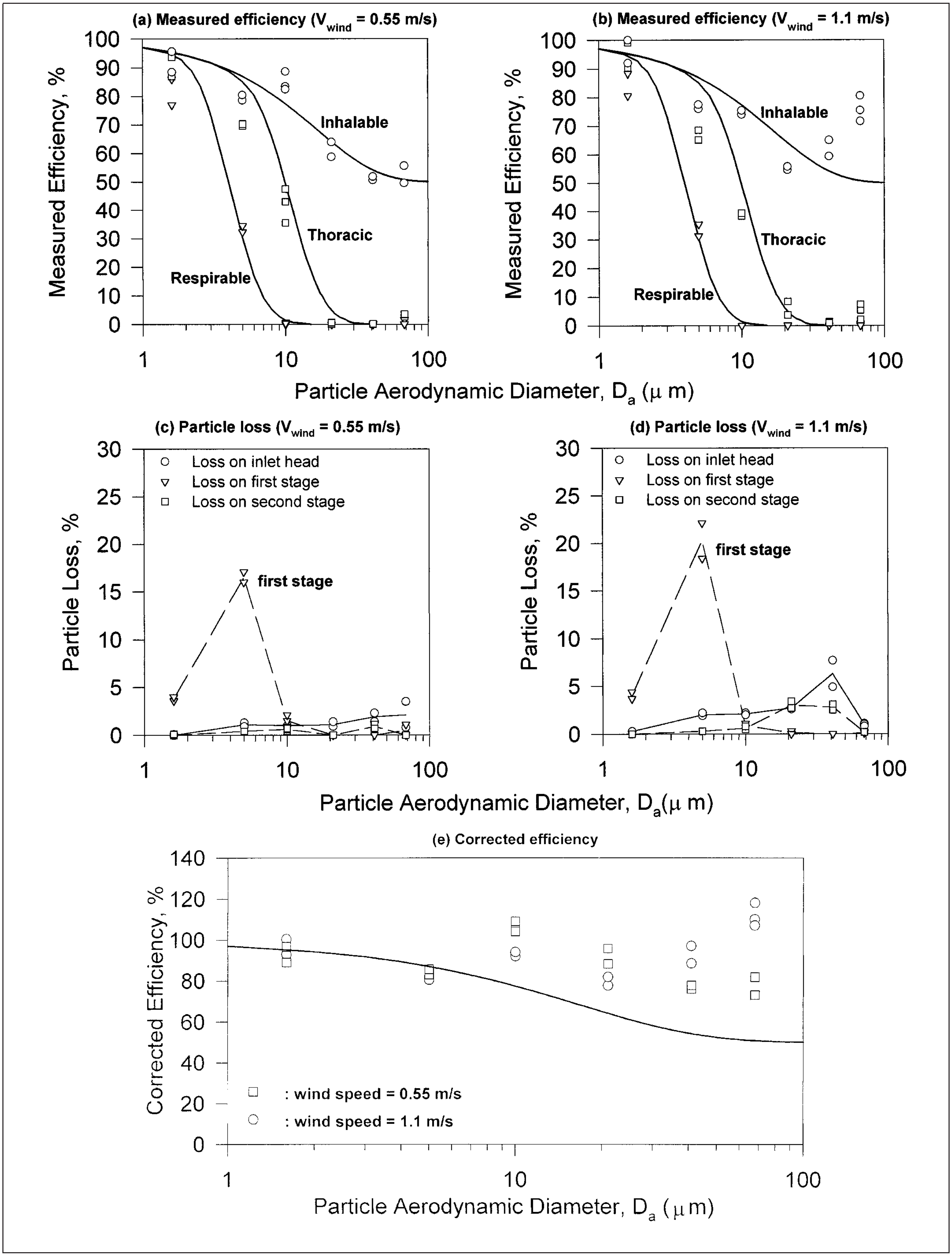
RespiCon Sampler

At a wind speed of 0.55 m/sec, the measured efficiencies of the RespiCon sampler, as shown in Figure 4a, match the inhalable convention. The differences between the average measured efficiencies and the inhalable convention are less than 10%. At a wind speed of 1.1 m/sec, as shown in Figure 4b, the performances of the RespiCon sampler fit the inhalable convention fairly well except for the 68-μm particles. The RespiCon oversampled the 68-μm particles by ~25%. A recent study by Baldwin and Maynard[7] shows that the average wind speed in indoor workplaces is 0.3 m/sec. Therefore, the test wind speed of 0.55 m/sec is closer to the average workplace wind speed.

Inside particle losses of the RespiCon sampler are shown in Figures 4c–4d. For 5 μm particles, the RespiCon sampler has particle losses of about 18% associated with the first stage nozzle, which has a cutpoint diameter of 4 μm (particle loss at 4 or 4.5 μm may even be higher). Theoretically, a virtual impactor has its peak particle losses near the cutpoint diameter at the tip of the receiving tube.[22] In this study, most inside losses of the 5-μm particles were found on the tip of the first receiving tube. To minimize the losses on the receiving tube, the diameter ratio between the receiving tube and the (first) nozzle should be between 1.35 and 1.40.[23] The diameter ratio for the first stage of the RespiCon is only 1.1 (3.2/2.9). The high particle losses could result in partial plugging of the receiving tube and performance change of the RespiCon sampler. Particle losses on the second stage were negligible. The low particle losses on the second stage could result from larger diameter ratio (3.0/2.5=1.2) and higher reentrainment of large particles. Particle losses inside the inlet head were low, which could also result from large particle reentrainment effects.

The measured efficiencies for the respirable and the thoracic fractions are shown in Figures 4a–4b. For the thoracic fraction, the performances of the RespiCon sampler match the thoracic convention very well except for the 5-μm particles. Undersampling of the 5-μm particles probably results from the high inner particle losses. With the addition of the 5-μm particle losses to the measured thoracic efficiency, the difference between the measured value and the thoracic convention would be less than 10%. For 68 μm particles, after the test, a small percentage of the particles was observed (using a light microscope) on the middle filter, which is intended to collect particles with D_a ranging from 4 to

Applied Studies


(a) Measured efficiency (V_wind = 0.55 m/s)
(b) Measured efficiency (V_wind = 1.1 m/s)
Measured Efficiency, %
Inhalable
Thoracic
Respirable
Particle Aerodynamic Diameter, D_a (μ m)
(c) Particle loss (V_wind = 0.55 m/s)
(d) Particle loss (V_wind = 1.1 m/s)
Loss on inlet head
Loss on first stage
Loss on second stage
first stage
Particle Loss, %
Particle Aerodynamic Diameter, D_a(μ m)
(e) Corrected efficiency
Corrected Efficiency, %
: wind speed = 0.55 m/s
: wind speed = 1.1 m/s
Particle Aerodynamic Diameter, D_a (μ m)

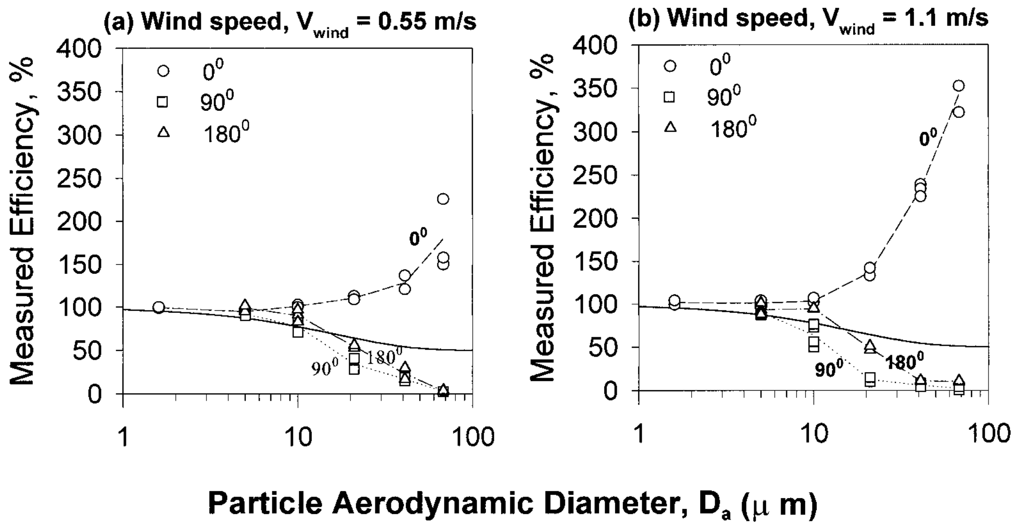


FIGURE 5. Measured efficiency of an IOM sampler at three wind orientations and two wind speeds. Solid line: inhalable convention.

10 μm. This 68 μm particle collection resulted in a slight deviation of the RespiCon performance from the thoracic convention. The reason the large particles were collected on the middle filter is not known.

The measured respirable efficiencies fit the respirable convention very well except for the 1.6-μm particles. Undersampling of the 1.6-μm particles resulted from the nonuniformity of the test particles. The 1.6-μm test aerosol has 17% of the particles with D_a greater than the cutpoint diameter (4 μm) of the respirable fraction.

In the operational manual of the RespiCon sampler, a correction factor of 1.5 is applied to the particles with diameters greater than the thoracic fraction (also called the extrathoracic fraction). The reason for introducing this correction factor was to comply with the German standards requiring an almost 100% efficiency up to 100 μm particles. When the correction factor was used, as shown in Figure 4e, the corrected efficiencies were much higher than the inhalable convention for particles with D_a greater than 10 μm. The 1.5 correction factor for the RespiCon sampler appears unnecessary for area sampling.

IOM Sampler

The aerosol measurement efficiencies of the IOM sampler at three wind orientations (0, 90, and 180°) and two wind speeds (0.55 and 1.1 m/sec) are shown in Figures 5a–5b. For 0° orientation (wind toward the sampler inlet), the measured efficiencies continuously increased from 100% as the particle D_a increased from 10 to 68 μm. For 90 and 180° orientations, the measured efficiencies continuously decreased from about 100% to nearly 0% as the particle D_a increased. Because the filter and the filter cassette are analyzed together in the IOM sampler, there is no inner particle loss.

For the sampling of inhalable aerosols, the IOM sampler oversampled the large particles (D_a greater than 20 μm) when the wind orientation was about 0° and undersampled the large particles when the wind orientations were 90 and 180°, as shown in Figures 5a and 5b. As the particle diameter increased, the difference between the inhalable convention and the measured efficiency of the IOM sampler increased.

Seven-Hole Sampler

The measured efficiencies for the seven-hole sampler, as shown in Figures 6a and 6b, were similar to those of the IOM sampler except for the test condition of 0.55 m/sec wind speed at 0° wind orientation, which has measured efficiencies gradually decreasing from 100% as the particle diameter increases. Similar to the IOM sampling performance, the seven-hole sampler oversampled the large inhalable particles (D_a greater than 20 μm) when the wind orientation was about 0° and undersampled the large inhalable particles when the wind orientations were 90 and 180°. The inside particle losses, as shown in Figures 6c and 6d, were nearly 0% for 90 and 180° orientations. For 0° orientation, the inside losses increase as the particle diameter increased.

Closed-Face 37-mm Cassette

Generally, the measured efficiencies for the cassette, as shown in Figures 7a and 7b, decreased from 100% as the particle diameter increased for all test wind conditions. For the sampling of particles with D_a greater than 30 μm, the closed-face 37-mm cassette has a measured efficiency lower than the inhalable convention in all three wind directions (0, 90, and 180°). As the particle diameter increased, the difference between the inhalable convention and the measured efficiency of the closed-face cassette increased. The inside particle losses, as shown in Figures 7c and 7d, were insignificant for 90 and 180° orientations. For 0° orientation, the inside losses had a steep increase for particles greater than 40 μm.

←

FIGURE 4. Measured efficiency (a and b), inside particle loss (c and d), and corrected efficiency (e) of a RespiCon sampler (solid line: inhalable convention). Note: the 1.6 μm test aerosol was not of a uniform size, and those data points need a correction factor.

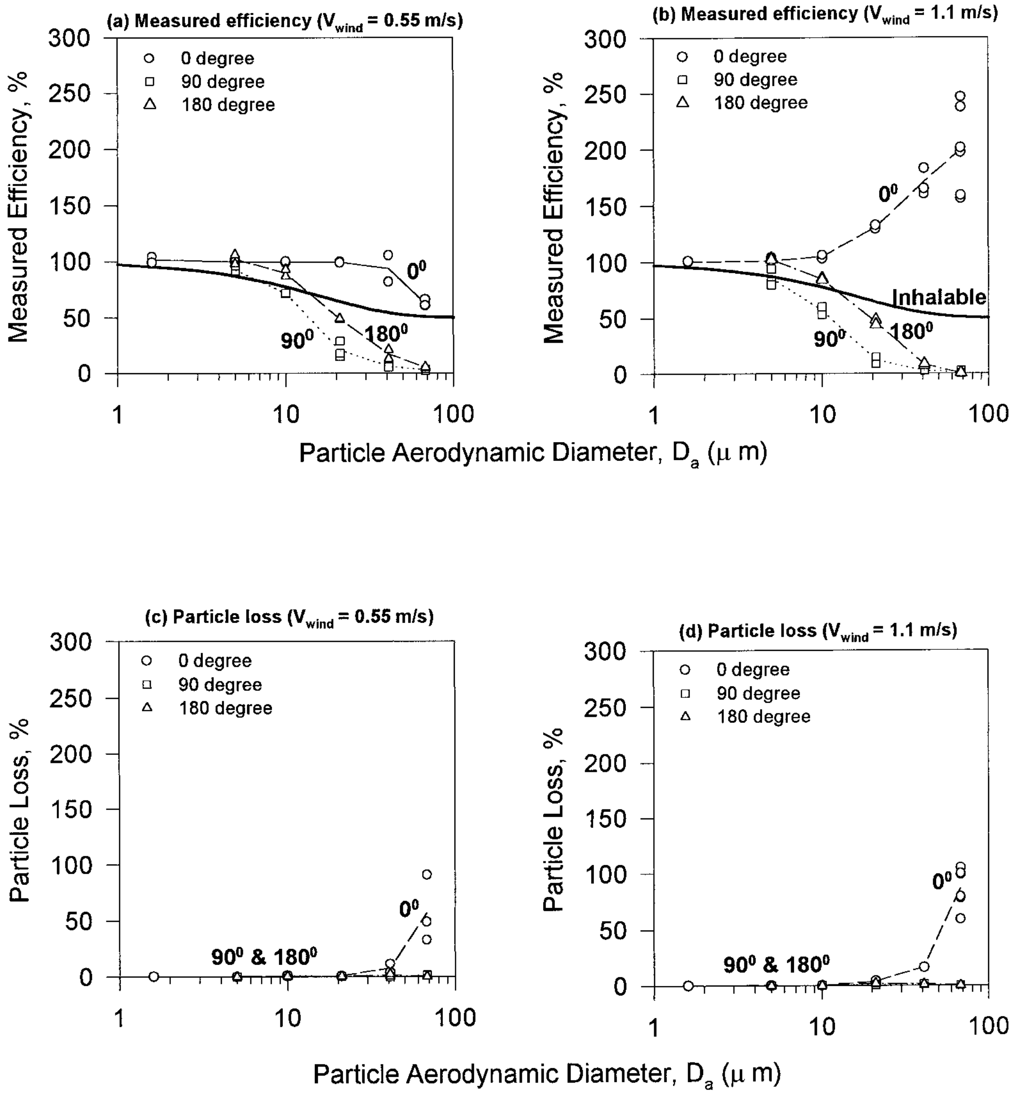


FIGURE 6. Measured efficiency and inside particle loss of a seven-hole sampler at three wind orientations and two wind speeds. Solid lines in (a) and (b): inhalable convention.

CIS Sampler

The measured efficiencies, as shown in Figures 8a and 8b, decreased from 100% as the particle diameter increased for all test wind conditions. For the sampling of particles with D_a greater than about 50 μm, the CIS sampler undersampled the inhalable aerosols for all test wind conditions. The inside particle losses, as shown in Figures 8c and 8d, were insignificant for 90 and 180° orientations. For 0° orientation, the inside losses increased as the particle diameter increased.

Prototype Button Sampler

For 0° wind orientation, the measured efficiencies, as shown in Figures 9a and 9b, have the maximum measured value at 41 μm. When the particle diameters were less than 10 μm, the measured efficiencies were fairly stable (from 87 to 98%). When the particle diameter increased from 41 to 68 μm, the measured efficiencies decreased. For 90 and 180° orientations, the measured efficiencies decreased from about 80 to nearly 0% as the particle diameter increased from 1.6 to 68 μm. Similar to the IOM and the seven-hole samplers, the prototype button sampler oversampled the large inhalable aerosols (D_a greater than 20 μm) when the wind direction was about 0°, and undersampled the large inhalable aerosols when the wind directions were 90 and 180°. The particle losses on the front gasket, as shown in Figures 9c and 9d, are insignificant except for large particles at the test condition of 1.1 m/sec wind speed, 0° wind orientation.

DISCUSSION

Among the six aerosol samplers tested as area samplers at wind speeds of 0.55 and 1.1 m/sec, only the RespiCon had a sampling performance that reasonably matched the inhalable convention. For the other five samplers, sampling performances were highly dependent on wind direction. For example, when sampling 68 μm particles at a wind speed of 0.55 m/sec, the IOM sampler had a measured efficiency of 180% for a 0° wind orientation, and

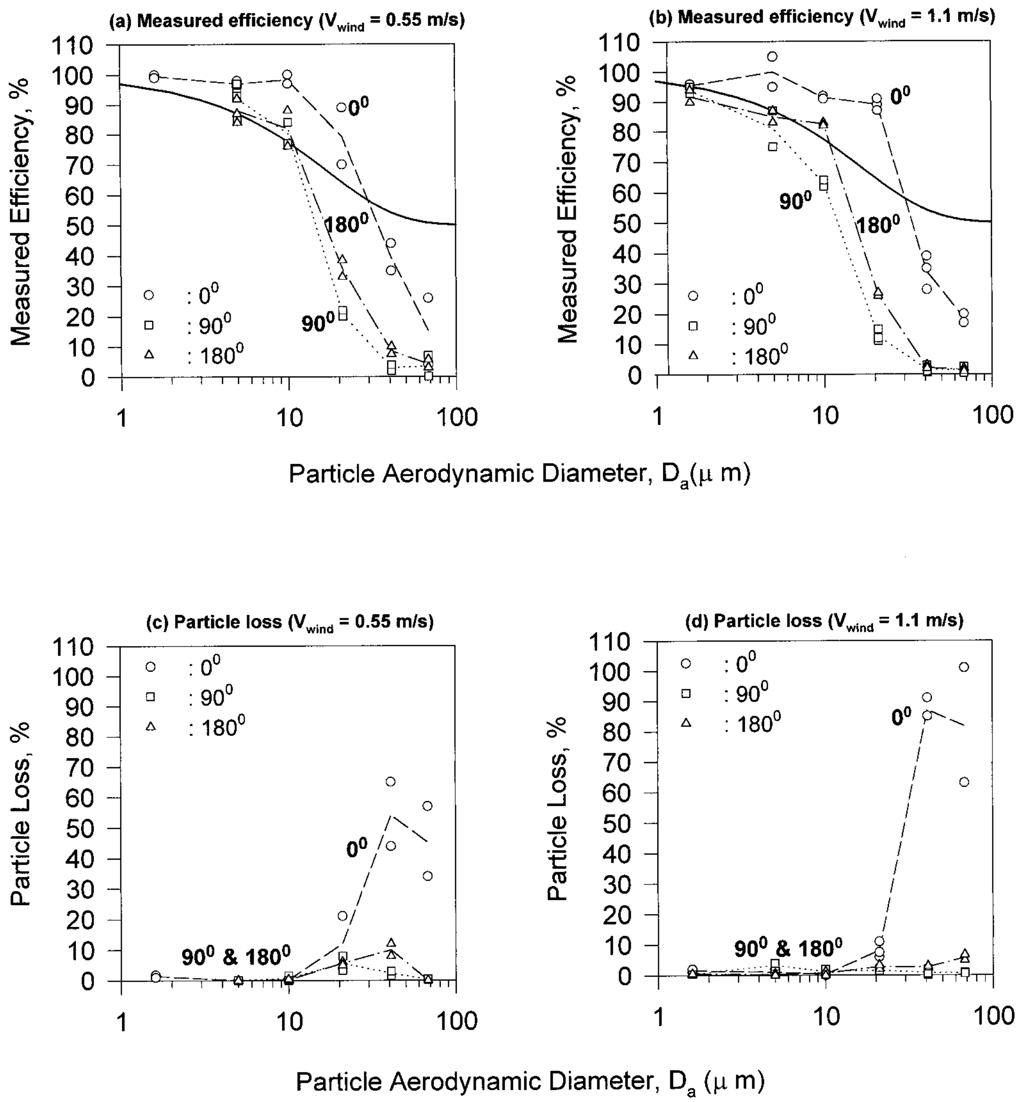


FIGURE 7. Measured efficiency and inside particle loss of a closed-face 37-mm cassette at three wind orientations and two wind speeds. Solid lines in (a) and (b): inhalable convention.

about a 3% sampling efficiency for 90 and 180° wind orientations. Generally, for the same particle diameter, the measured efficiency for 0° has the highest value, and the measured efficiency for 180° is greater than that for 90°. For large particles (e.g., 50 μm D_a) in moderate air velocity (~1 m/sec), concentration measurements could vary by a factor of 2 to 10 because of sampler orientation.

In this study, it was found that the closed-face 37-mm cassette, CIS sampler, and seven-hole sampler had high inside particle losses for large particles. To obtain some insight into this problem, only the central area (~20 mm) of the 37-mm filters in the closed-face cassette and the CIS sampler were coated with petroleum jelly to collect and prevent bouncing off the 41-μm particles at the test condition of 1.1 m/sec wind speed, 0° wind orientation. With the greased filters, the inside particle losses of the 37-mm cassette decreased from 87 to 1%, and the inside losses of the CIS sampler decreased from 42 to 15%. This means that most of the large solid particles entering the closed-face 37-mm cassette hit the filter and bounce off, which results in the low measured efficiency. High inner particle losses of the closed-face 37-mm cassette were also found by Moore et al.[24] during wood-dust sampling. For the CIS sampler, about two-thirds of the inside large-particle losses are due to the particle bounce-off and one-third of the losses are due to gravity settling. Therefore, when these three samplers are used as personal or area samplers, their sampling performances will depend on the stickiness of the sampled particles. For example, for the same particle diameter, the measured efficiency of solid particles will be less than that of liquid particles (approximates to the measured efficiency plus particle loss for the solid particles).

To give a better understanding of the inlet performances, the total (inlet) efficiency, summation of the measured efficiency, and the inside loss of four aerosol samplers at 0° wind orientation are plotted in Figures 10a and 10b. Generally, at 0° wind orientation the total efficiency increases as the velocity ratio (R), V_{wind}/V_i (V_{wind} : wind velocity, V_i : inlet velocity), increases. When R is greater than 1, the total efficiency increases from 100% as the

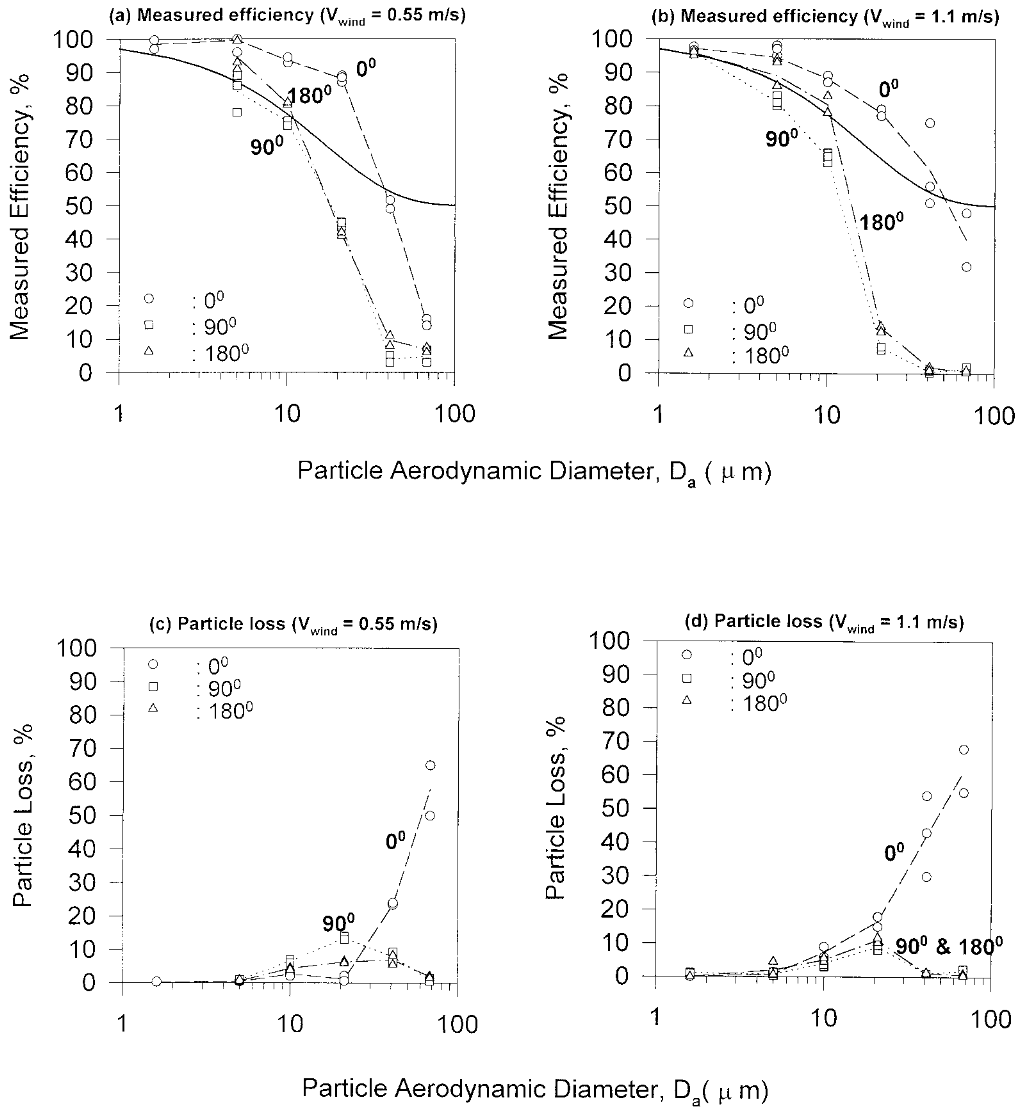


FIGURE 8. Measured efficiency and inside particle loss of a CIS sampler at three wind orientations and two wind speeds. Solid lines in (a) and (b): inhalable convention.

particle diameter increases; on the other hand, when R is less than 1, the total efficiency decreases from 100% as the particle diameter increases. When R is close to 1, as shown in the CIS curve of Figure 10b, the total efficiency is almost a constant line of 100%. However, for large particles the total efficiency of the closed-face 37-mm cassette is slightly greater than 100% even though R is less than 1. That could result from the reentrainment of large particles depositing on the outside surfaces of the closed-face cassette. Theoretically, for the particles of infinite inertia, the total efficiency will asymptotically approach the R value. For example, at a wind speed of 0.55 m/sec, the IOM sampler had an R value of 2.9; therefore, the maximum total efficiency of the IOM will be 290%. The total efficiencies of the RespiCon and the prototype button sampler are not plotted in Figure 10 due to their unique inlet geometries and performances. For 90 and 180° wind orientations, since the inside losses are insignificant, the total efficiency will be close to the measured efficiency; the measured efficiency (~total efficiency), as shown in Figures 5–8, decreased as the particle diameter increased for all four samplers (IOM, seven-hole, CIS, and closed-face 37-mm cassette). At the same testing condition, the total inlet efficiency difference among these four samplers was less than ~20% for 90 and 180° wind orientations.

To further understand the effect of wind orientation on total efficiency, an IOM sampler was tested at 30° intervals from 0 to 180° using monodisperse solid particles of 21 μm at a wind speed of 1.1 m/sec. As shown in Figure 11, the total efficiency continuously decreased from 0 to 90° and stayed fairly constant from 90 to 120°. From 120 to 180°, the total efficiency slowly and continuously increased. As the sampler was rotated from 0 to 90°, the effective inlet area continuously decreased, which decreased the inlet (or total) efficiency. When the sampler was further rotated from 90 to 180°, at a certain angle greater than 120°, the sampler body induced a particle-trapping turbulence around the sampler inlet, which resulted in the inlet efficiency increase.

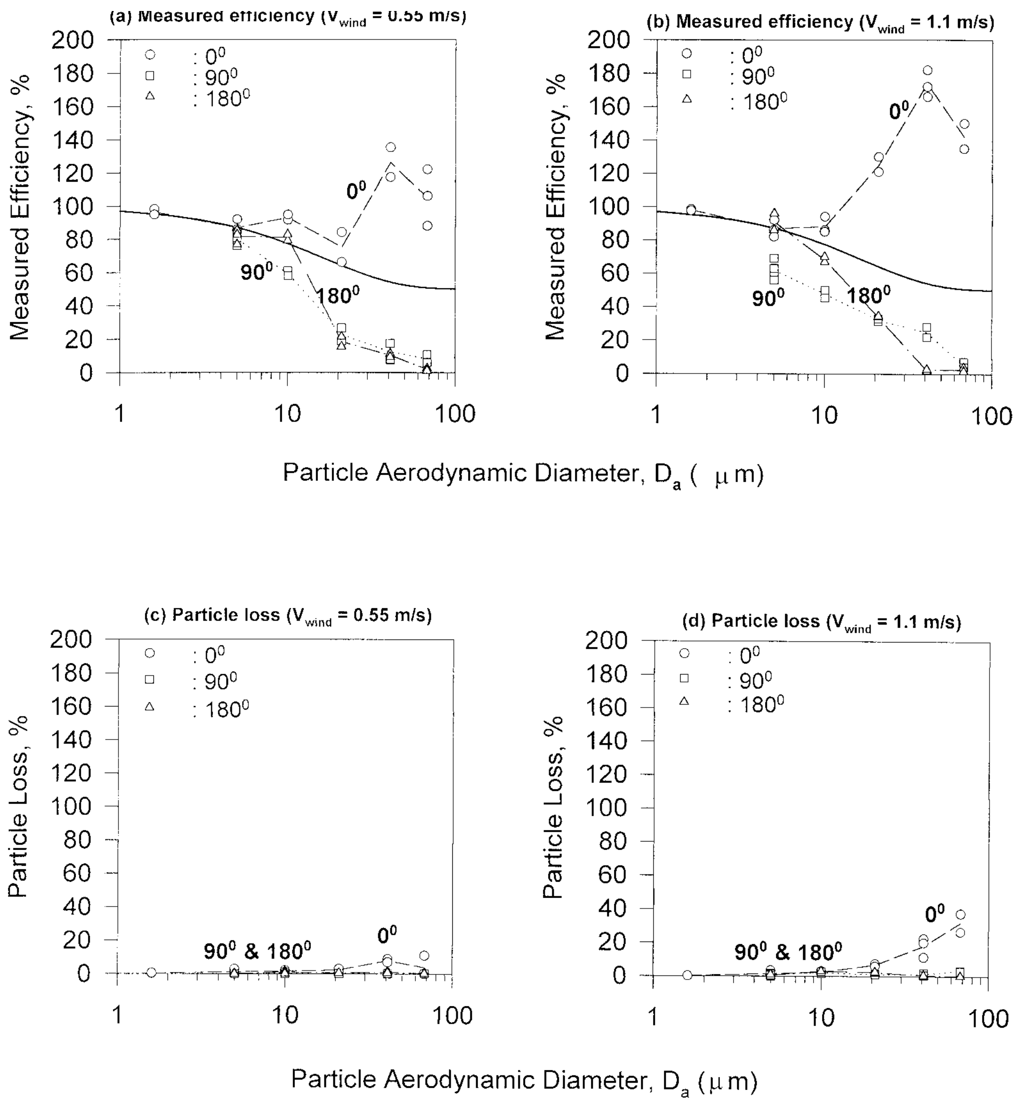


FIGURE 9. Measured efficiency and inside particle loss of a prototype button sampler at three wind orientations and two wind speeds. Solid lines in (a) and (b): inhalable convention.

Data point variations shown in Figures 4–11 are generally less than 20% for particles less than 41 µm. The variation usually increases as the particle diameter increases. For 68-µm particles, the variations are relatively high. This probably resulted from the nonuniform mixing of large particles due to the mixing plate removal. Errors due to the background (fluorocein) particles, particle recovery, uniformity of particle size, and sampling flow rate variations were found to be insignificant. Measurement variability was probably due to aerosol concentration variation.

CONCLUSIONS

In this study six inhalable aerosol samplers were tested (as area samplers) using monodisperse solid particles at different wind conditions. Their sampling performances were compared with the inhalable convention. The RespiCon sampler provided a reasonable match of the inhalable convention (if the manufacturer correction factor of 1.5 is not used). However, particle losses inside the RespiCon sampler should be closely monitored (and the unit cleaned) to prevent plugging of the first receiving tube.

The area sampling performances of the IOM, seven-hole, CIS, closed-face 37-mm cassette, and the prototype button sampler all are highly dependent on wind orientation, wind speed, and particle size. When the measured sampling efficiency was compared with the inhalable convention, the IOM, seven-hole, and prototype button sampler oversampled the large particles (D_a greater than 20 µm) when the wind direction was about 0° and undersampled the large inhalable particles when the wind directions were 90 and 180°. The difference between the inhalable convention and the sampler-measured efficiency increased as the particle diameter increased for all test wind conditions. The closed-face 37-mm cassette and the CIS sampler undersampled large inhalable particles ($D_a > 41$ µm) in all three wind directions (0, 90, 180°). The measured sampling performances of the closed-face 37-mm

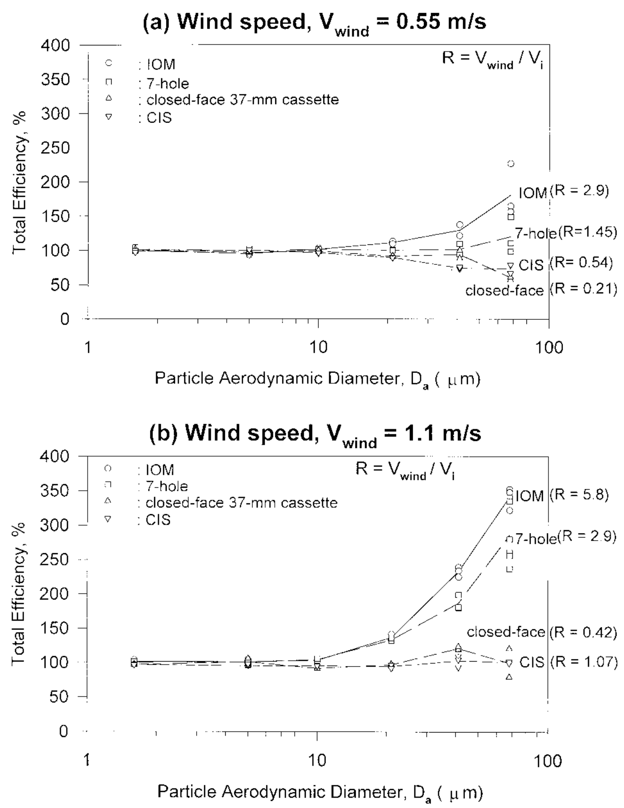


FIGURE 10. Effects of velocity ratio, V_{wind}/V_i (inlet velocity), on total efficiencies of four aerosol samplers at 0° wind orientation. (a) Wind speed = 0.55 m/sec; (b) wind speed = 1.1 m/sec.

cassette, CIS, and seven-hole sampler, whether used as area or personal samplers, also depend on the stickiness of the sampled particles because internal losses are highly variable for the larger (20 to ~100 μm) particles.

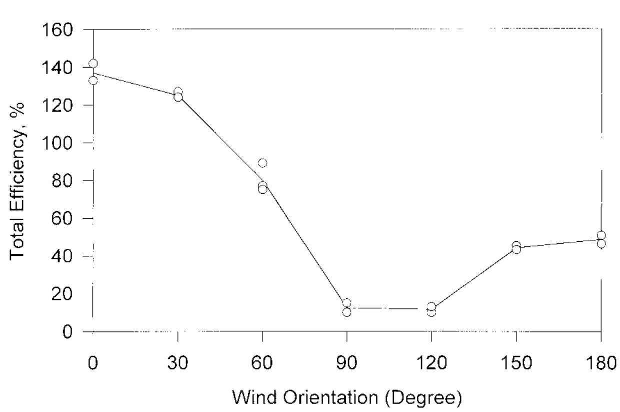


FIGURE 11. Effect of wind orientation on total inlet efficiency of an IOM sampler. Wind speed = 1.1 m/sec, particle D_a = 21 μm.

REFERENCES

1. **Whitehead, L.W.:** Health effects of wood dust—relevance for an occupational standard. *Am. Ind. Hyg. Assoc. J. 43*:674–678 (1982).
2. **Vincent, J.H., and D. Mark:** Applications of blunt sampler theory to the definition and measurement of inhalable dust. *Ann. Occup. Hyg. 26*:3–19 (1982).
3. **Armbruster, L., and H. Breuer:** Investigations into defining inhalable dust. *Ann. Occup. Hyg. 26*:21–32 (1982).
4. **American Conference of Govermental Industrial Hygienists (ACGIH):** *Threshold Limit Values for Chemical Substances and Physical Agents and Biologiacal Exposure Indices.* Cincinnati, OH: ACGIH, 1995.
5. International Organization for Standardization (ISO): *Air Quality—Particle Size Fraction Definition for Health-Related Sampling* (ISO CD7708). Geneva: ISO, 1992.
6. **Comité Européen de Normalisation (CEN):** *Workplace Atmosphere: Size Fraction Definitions for Measurement of Airborne Particles in the Workplace* (CEN Standard EN 481). Brussels: CEN, 1992.
7. **Baldwin, P.E.J., and A.D. Maynard:** A survey of wind speeds in indoor workplaces. *Ann. Occup. Hyg. 42*:303–313 (1998).
8. **Aitken, R.J., P.E.J. Baldwin, G.C. Beaumont, L.C. Kenny, and A.D. Maynard:** Aerosol inhalability in low air movement environments. *J. Aerosol Sci. 30*:613–626 (1999).
9. **Kenny, L.C., R.J. Aitken, C. Chalmers, J.F. Fabriés, et al.:** a collaborative European study of personal inhalable aerosol sampler performance. *Ann. Occup. Hyg. 41*:135–153 (1997).
10. **Kenny, L.C., R.J. Aitken, P.E.J. Baldwin, G.C. Beaumont, and A.D. Maynard:** The sampling efficiency of personal inhalable aerosol samplers in low air movement environments. *J. Aerosol Sci. 30*:627–638 (1999).
11. **Buchan, R.M., S.C. Soderholm, and M.I. Tillery:** Aerosol sampling efficiency of 37-mm filter cassettes. *Am. Ind. Hyg. Assoc. J. 47*:825–831 (1986).
12. **Chung, K.Y.K., T.L. Ogden, and N.P. Vaughan:** Wind effects on personal dust samplers. *J. Aerosol Sci. 18*:159–174 (1987).
13. **Rodes, C.E., R.M. Kamens, and R.W. Wiener:** Experimental considerations for the study of contaminant dispersion near the body. *Am. Ind. Hyg. Assoc. J. 56*:535–545 (1995).
14. **Tsai, P.-J., and J.H. Vincent:** Impaction model for the aspiration efficiencies of aerosol samplers at large angles with respect to the wind. *J. Aerosol Sci. 24*:919–928 (1993).
15. **Witschger, O., K. Willeke, S.A. Grinshpun, V. Aizenberg, J. Smith, and P.A. Baron:** Simplified method for testing personal inhalable aerosol samplers. *J. Aerosol Sci. 29*:855–874 (1998).
16. **Vincent, J.H.:** *Aerosol Science for Industrial Hygienists.* New York: Elsevier Science, 1995.
17. **American Industrial Hygiene Association (AIHA):** *Particle Size-Selective Aerosol Sampling in the Workplace.* Fairfax, VA: AIHA, 1996.
18. **Koch, W., W. Dunkhorst, and H. Lödding:** Design and performance of a new personal aerosol monitor. Manuscript submitted for publication, 1999.
19. **Mark, D., and J.H. Vincent:** A new personal sampler for airborne total dust in workplaces. *Ann. Occup. Hyg. 30*:89–102 (1986).
20. **Kalatoor, S., S.A. Grinshpun, K. Willeke, and P. Baron:** New aerosol sampler with low wind sensitivity and good filter collection uniformity. *Atmos. Environ. 29*:1105–1112 (1995).
21. **Rubow, K.L., V.A. Marple, J. Olin, and M.A. McCawley:** A personal cascade impactor: Design, evaluation and calibration. *Am. Ind. Hyg. Assoc. J. 48*:532–538 (1987).
22. **Marple, V.A., and C.M. Chien:** Virtual impactors: A theoretical study. *Environ. Sci. Technol. 14*:976–984 (1980).
23. **Loo, B.W., and C.P. Cork:** Development of high efficiency virtual impactors. *Aerosol Sci. Technol. 9*:167–176 (1988).
24. **Moore, L.L., D.J. Dube, and T. Burk:** Improved sampling and recovery of wood dust using MSA respirable dust cassettes. *Am. Ind. Hyg. Assoc. J. 51*:A475–A476 (1990).