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NEW AEROSOL SAMPLER WITH LOW WIND SENSITIVITY AND GOOD FILTER COLLECTION UNIFORMITY

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Abstract—The overall sampling efficiency of many aerosol samplers is sensitive to wind velocity and direction. In addition, most samplers have internal losses due to gravitational settling, electrostatic interactions, and internal turbulence. A new sampling inlet has been designed to reduce these problems. The flow patterns over the new prototype sampler were visualized in a horizontal wind tunnel. Visualization of the streamlines over the new sampler and limiting-streamline quantitative analysis showed negligible turbulence effects due to the inlet's geometry. The overall sampling efficiency of the prototype sampler was compared to that of a 25 mm closed-face cassette. Uranine was used as the challenge aerosol with particle physical diameters of 13.5, 20 and 30 μm. The wind velocity ranged from 100 to 300 cm s^{-1}. Evaluation of the data showed the new sampler to be less significantly affected by wind direction and magnitude. The particle distribution observed on the sampler's filter was found to be reasonably uniform, an advantage for several types of analyses.

Key word index: Personal sampler, particle losses, particle distribution, sampling efficiency, inlet.

INTRODUCTION

A variety of aerosol samplers is available for collecting particles onto a filter. The flow rate through a sampler and filter is usually established according to the specifications of the sampling method and is held constant so that an accurate sample and representative volume can be determined. Stationary aerosol samplers are used to evaluate both outdoor environment and indoor work environments. Personal breathing zone samplers worn by workers are used to estimate their exposures to workplace pollutants. The inlets of commercially available sampler have evolved to measure the aerosol concentrations in different environments. Several researchers have reported that significant biases (primarily particle losses) may occur during aspiration into a sampler and during transmission of aerosols through the sampler (Ogden and Birkett, 1978; Beaulieu *et al.*, 1980; Kucharski, 1980; Mark *et al.*, 1985; Mark and Vincent, 1986; Vincent, 1989; Baron and Deye, 1990; Mark, 1990; Vaughan *et al.*, 1990; Willeke and Baron, 1990; Botham *et al.*, 1991; Willeke and Baron, 1993). These biases are sensitive to the magnitude and direction of the ambient air velocity. In indoor work environments, where the air velocity typically ranges from 100 to 300 cm s^{-1} (Mark, 1990), the external geometry of a sampling cassette may influence the flow pattern in the vicinity of the sampler's inlet, thereby adversely affecting the sampler's performance.

Sampling efficiency

The sampling efficiency of a sampler, E_s, is defined as the ratio of the sampled particle concentration, C_s, to the environmental particle concentration, C_o:

$$E_s = \frac{C_s}{C_o}. \tag{1}$$

To determine C_o, it is important that the inlet efficiency be evaluated under a range of controlled operating conditions. Particle size distribution, wind velocity U_w, inlet velocity U_i, inlet shape, particle density, and inlet orientation with respect to the wind

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and gravitational force are some of the factors which affect sampling efficiency.

For isoaxial sampling, the velocity ratio R, which is the ratio of the wind to the inlet velocity, determines whether the sampling is isokinetic ($R = 1$), sub-isokinetic ($R > 1$) or super-isokinetic ($R < 1$). During isokinetic sampling, the limiting stream-surface flows into the inlet without a change in direction, and the particle concentration at the face of the inlet is equal to C_o. During non-isokinetic aspiration, particle inertia may lead to the migration of some particles across the limiting stream-surface, resulting in a different aerosol concentration at the face of the inlet (Badzioch, 1959; Belyaev and Levin, 1972, 1974).

For a tubular, thin-walled inlet, overall sampling efficiency consists of two major components — aspiration efficiency, E_a, and transmission efficiency, E_t:

$$E_s = E_a E_t. \tag{2}$$

Because of the complex geometry of many aerosol samplers and the unstable wind conditions present in most environments, it is usually difficult to exactly quantify sampling efficiency. Most of the available experimental data are for thin-walled tubular inlets. Most of the equations developed from theory or empirically from experimental data are valid only for a specific set or range of conditions. Attempts to develop universal equations for aerosol aspiration and transmission that satisfy a wind range of sampling regimes have been made by several authors (Vincent, 1989; Hangal and Willeke, 1990a; Hangal and Willeke, 1990b). The general aerosol aspiration equation by Grinsphun *et al.* (1993), is valid for a wide range of ambient wind conditions—from calm-air to fast-moving air.

The main function of a sampler is to ensure that all or most of the particles in a given volume of ambient air are aspirated to the inlet and reliably transported onto a filter or through a dynamic sensor for analysis. The external geometry of the sampler may significantly affect aspiration efficiency (Dunnett and Ingham, 1988). Particles may be lost during transmission through the sampler due to one or more physical mechanisms, such as direct wall impaction and gravitational settling (Okazaki *et al.*, 1987a, b), migration in the developing boundary layer (Okazaki *et al.*, 1987a; Hangal and Willeke, 1990b), and electrostatic deposition (Baron and Deye, 1990). For a tubular sampling inlet, the majority of particles is lost in the first two diameters of the sampler (Tufto and Willeke, 1982a). The main reason for such particle losses in the entrance region of a sampling inlet is the formation of a vena contracta (for $R < 1$) and impaction of particles to the inner wall of the inlet. Thus, the concentration of particles collected on a filter or passed through a sensor is generally less than the aspirated particle concentration.

If there is a long distance between the entrance region and the sensor or collection surface, additional losses may occur, mainly due to gravitational settling and electrostatic deposition of particles (Whitby and Liu, 1968). Gravitational settling depends on particle settling velocity and the distance from the inlet face to the filter or sensor surface. Electrostatic deposition depends on the electric charge on the particles and the electrical conductivity of the sampler's surfaces.

In workplace environments, the protection of the workers' health is of primary importance and as such the size and concentration of the particles that can be inhaled by a person is of concern. Rather than attempting to sample "total dust", optimum sampling was defined on the basis of the efficiency of human breathing (Mark *et al.*, 1985). The sampling efficiency for particles larger than 30 μm was set at 50%. However, only limited information is available regarding the collection efficiency of particles larger than 20 μm for currently used samplers. As standards are being developed for inhalable particles (American Conference of Governmental Industrial Hygienists, 1993; International Standards Organization, 1983; Soderholm, 1993), development of better samplers that reduce the problems associated with currently available samplers is desirable. Vincent and co-workers at the Institute of Occupational Medicine, Edinburgh, U.K. (Vincent, 1989) have developed an inhalable sampler that matches the inhalable curves better than all other samplers tested. However, this sampler has an open-faced inlet which makes it prone to collection of large particles ($\geqslant 100$ μm) that are not considered inhalable. In addition, open-faced samplers can give non-uniform filter deposits, which are desirable in some situations (Baron *et al.*, 1994). Improved samplers will lead to better and more consistent determinations of workers' exposures to occupational dust and consequently to better control of these contaminants.

NEW SAMPLER DESIGN

When designing a new aerosol sampler, factors that influence its performance need to be considered, i.e. particle size, wind velocity, wind direction, aerosol composition, aerosol concentration, particle charge, ambient temperature, ambient pressure, ambient humidity, vibration, air current disturbances, and orientation. In this study we address the following parameters that have a pronounced effect on sampling efficiency and the distribution of particles on the collection surface: wind velocity and direction.

One embodiment of the new sampler is schematically shown in Fig. 1. The inlet is formed from a portion of a spherical shell with numerous, identical, evenly spaced holes that act as sampling orifices and give the sampler multidirectional sampling capability. The parameters that were considered while designing the sampler were the subtended angle of the spherical surface (ω), filter diameter, porosity of the spherical surface, orifice diameter and sampling flow rate. The filter is directly behind the inlet to avoid transmission losses in the sampler. The uniform distribution of the

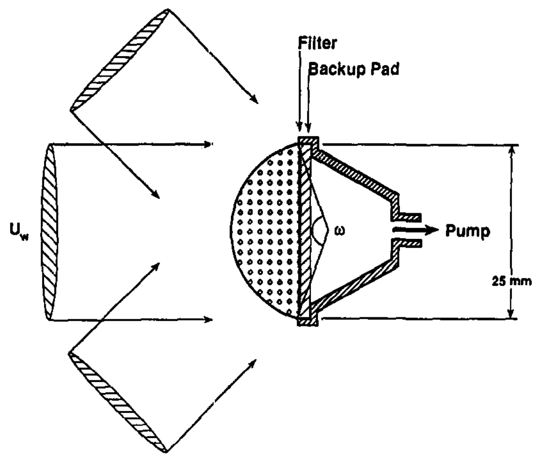

Fig. 1. Schematic diagram of the new aerosol sampler with multi-directional sampling capability.

orifices on the curved inlet surface contributes to the uniform distribution of sampled particles on the filter surface.

This new design can be used for ambient air sampling and for personal breathing zone sampling. For the latter, the airflow is withdrawn laterally after the filter (90° to the outlet port in Fig. 1), so that the sampler protrudes a minimum distance from the wearer's clothing. In this study, the following sampling parameters were chosen for workplace environmental conditions: the flow rate was fixed at $2\,\ell\,\mathrm{min}^{-1}$ (this is a common flow rate for measuring worker exposure which is readily achievable by personal sampling pumps) and a filter diameter of 25 mm was chosen (this size filter is used in work environment sampling).

The air velocity through the orifice of the curved inlet surface has to be high enough to create enough pressure drop for even flow distribution, and the orifice hole size has to be large enough to allow the largest particles to pass through without significant wall losses caused by interception. In addition to interception, inertial particle deposition was evaluated using available aerosol filtration models (Willeke and Baron, 1993). Inertial deposition losses on the inlet surface were found to reduce the efficiency of particle penetration through the inlet screen when sampling larger particles. This may affect the new sampler performance characteristics, especially when sampling liquid droplets (when sampling solid particles some of them may bounce from the inlet surface, be re-entrained into the entering airstream and be collected on the filter). It was decided that the orifice diameters should be at least five times the largest particle diameter tested, i.e. 150 μm, to the meet this condition. The physical diameters of the particles used

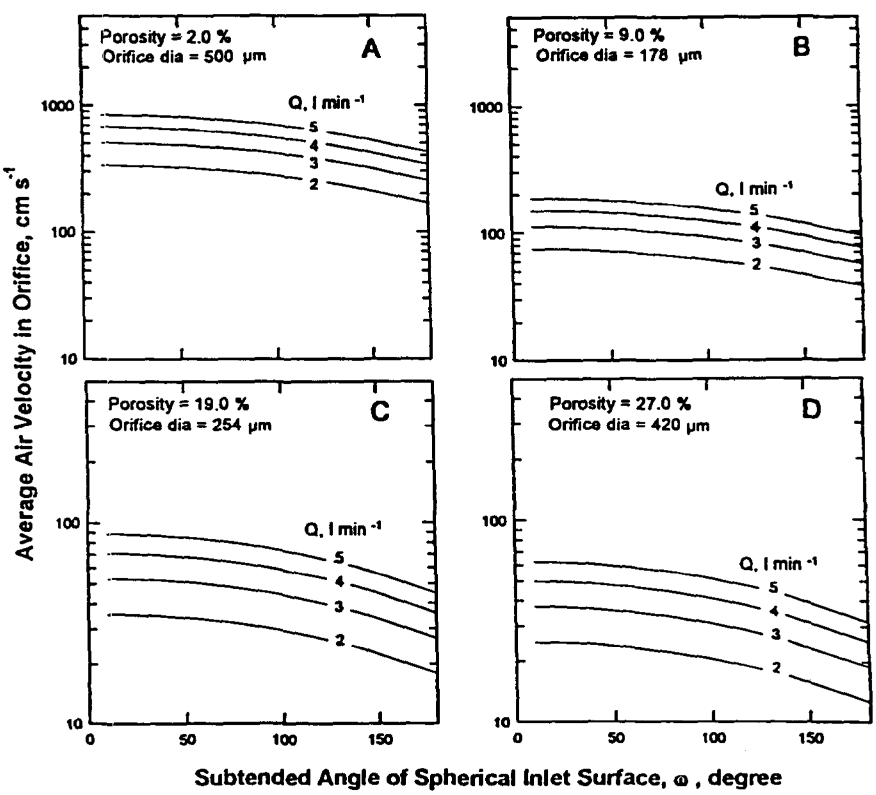

Fig. 2. Calculated air velocities in evenly spread circular orifice in a spherical inlet surface, filter diameter = 25 mm.

in our study ranged from 13.5 to 30 μm (corresponding aerodynamic diameters = 17–38 μm). Due to the limitation of the dynamic measurement of particle concentration, larger particles could not be efficiently detected, especially at lower wind velocities. Figure 2 shows the calculated average air velocities from available metal sheets with different porosity and orifice sizes. As a compromise between inlet velocity and orifice diameter, a metal sheet with a 19% porosity and orifice diameters of 254 μm was formed into a spherical inlet with a subtended angle of 140°. The spherical shell was formed using a specially machined die and an available micro-etched stainless steel screen, made by Buckbee-Mears Co., St. Paul, MN. The average air velocity through these orifices is 25 cm s^{-1} for a 2 ℓ min^{-1} flow rate through a 25 mm diameter filter, Fig. 2C. The curved inlet was made of steel, since a conductive surface is expected to minimize electrostatic losses when sampling charged particles (Baron and Deye, 1990).

LABORATORY EVALUATION OF NEW SAMPLER

The performance evaluation of the prototype sampler was conducted in three parts. The first part of the evaluation was flow pattern visualization and quantitative analysis of the sampler aspiration efficiency, which was achieved by determining the limiting streamlines in a two-dimensional plane using tobacco smoke in a low-velocity wind tunnel. In the second part of the evaluation, overall sampling efficiency was measured for large solid particles in a horizontal high-velocity aerosol wind tunnel. In the third part, filter deposits were microscopically analyzed for distribution uniformity on the collection surface.

FLOW PATTERN VISUALIZATION AND QUANTITATIVE ANALYSIS

Method

Flow pattern visualization near a sampling inlet and determination of the aspiration efficiency by the limiting streamline method is generally performed only on a sampler with a single opening of either circular or rectangular cross section. We have applied this limiting streamline method to the multiple sampling point surface of the inlet face in order to qualitatively evaluate the turbulence in the sampling zone. The new sampler was tested in a low-velocity wind tunnel with a 20 cm diameter cross-section of transparent plexiglass. A porous foam plug and a honeycomb flow straightener were installed upstream of the sampler to obtain uniform flow in the wind tunnel. A fine stream of tobacco smoke was injected into the test section at a velocity that was approximately equal to that of the wind. A laser beam light sheet illuminated the smoke streamlines, and photographic images were captured on video tape for further analysis. Because the particle size of tobacco smoke is less than 2 μm (Xu et al., 1994), the influence of particle inertia was assumed negligible, and the trajectories of the smoke particles were assumed to equal those of the air streamlines. Two cases of sampler orientation were

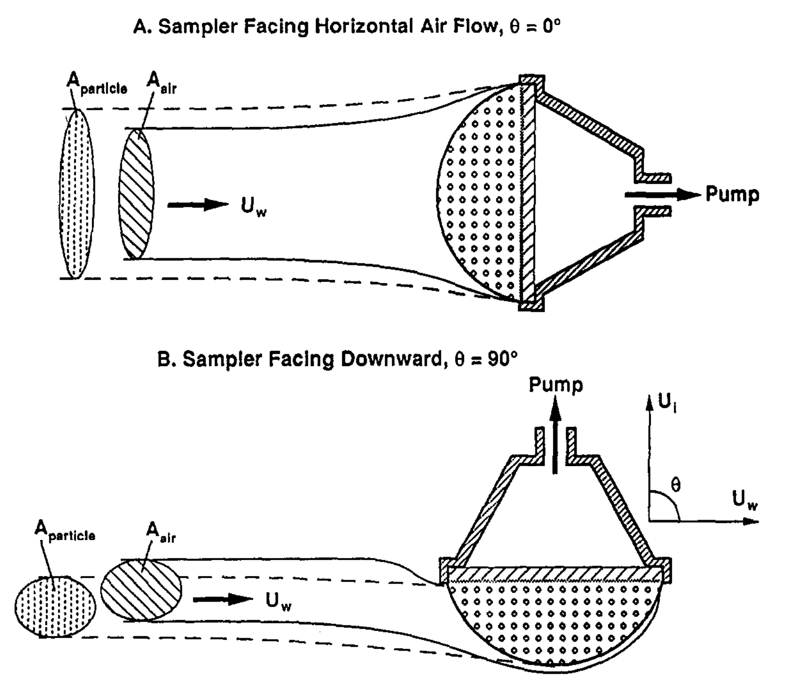

Fig. 3. Schematic representation of the limiting streamlines and particle trajectories for the two inlet orientations.

analyzed, isoaxial ($\theta = 0$) and downward facing ($\theta = 90°$), as schematically shown in Fig. 3.

For the limiting streamline analysis, the aspiration efficiency, E_a, has been defined as

$$E_a = \frac{N/V_{air}}{N/V_{particle}} = \frac{V_{particle}}{V_{air}} \quad (3)$$

where N is the number of particles passing through the inlet face, V_{air} is the sampled air volume and $V_{particle}$ is the upstream volume of air from which particles are aspirated. The sampled air volume is related to the upstream cross-sectional area of the limiting streamline surface, A_{air}.

$$V_{air} = A_{air} U_w t = A_i U_i t = Qt \quad (4)$$

where A_i is the cross-sectional area of the inlet and Q is the sampling flow rate. Similarly,

$$V_{particle} = A_{particle} U_w t \quad (5)$$

where $A_{particle}$ is the upstream cross-sectional area from which particles are aspirated. For inertialess particles, such as the smoke particles used in the tests, $A_{particle}$ is expected to equal A_{air}. $A_{particle}$ was measured from the images captured on video tapes for both sampling situations. For isoaxial sampling, Fig. 3A, $A_{particle}$ was assumed to be circular. For the sampler facing downward, Fig. 3B, $A_{particle}$ was assumed to be elliptical.

Results and discussion

A_{air} and $A_{particle}$ were determined for the same flow rate, wind velocity, and wind orientation. As an example, A_{air} for isoaxial sampling is $1.6\ cm^2$ for a flow rate of $2\ \ell\ min^{-1}$ and a wind velocity of $20\ cm\ s^{-1}$. $A_{particle}$ from images of the smoke streams, obtained under the same conditions, measured approximately $1.5\ cm^2$. For $\theta = 90°$, at a flow rate of $2\ \ell\ min^{-1}$ and a wind velocity of $50\ cm\ s^{-1}$, the upstream projected elliptical cross-sectional area for the limiting stream surface was calculated to be $0.66\ cm^2$ while the smoke images under the same conditions resulted in $A_{particle} = 0.70\ cm^2$. Equality of A_{air} and $A_{particle}$ within experimental accuracy, which was expected, confirms the suitability of the techniques used for the flow pattern visualization.

Visualization of the smoke streamlines over the prototype sampler showed negligible turbulence effects due to the inlet geometry. This qualitative observation demonstrates an important feature of the new inlet design. The flow into the inlet followed a smooth curve even when the prototype sampler was placed at 90° to the horizontal wind direction. This behavior shows an advantage over other types of samplers where the streamlines do not enter the inlet smoothly and may thus affect the aspiration efficiency (Baron *et al.*, 1994).

OVERALL SAMPLING EFFICIENCY

Method

The second part of the laboratory evaluation was performed using a horizontal high-velocity aerosol wind tunnel (Tufto and Willeke, 1982b). The performance characteristics of the sampler were compared with a widely used and commercially available personal breathing zone sampler used for workplace analysis. A closed-face 25 mm personal sampling filter cassette with a 4 mm inlet was chosen for comparison (Buchan *et al.*, 1986).

Monodisperse particles of uranine (sodium fluorescein) with physical diameter 13.5, 20 and 30 μm (aerodynamic diameter $d_{ae} = 17$, 26 and 38 μm) were used as test aerosols. The monodisperse particles were generated by means of a vibrating orifice aerosol generator (Berglund and Liu, 1973). The available aerosol delivery system and the wind tunnel (Wiener *et al.*, 1988) were modified for drying and transport of the large aerosol particles to the test section using methods developed by Vanderpool and Rubow (1988).

To confirm the size and shape of the generated aerosol particles, the test particles were first sampled onto a fibrous filter pad that was rigidly suspended in the test section. Since solid dry aerosols do not create

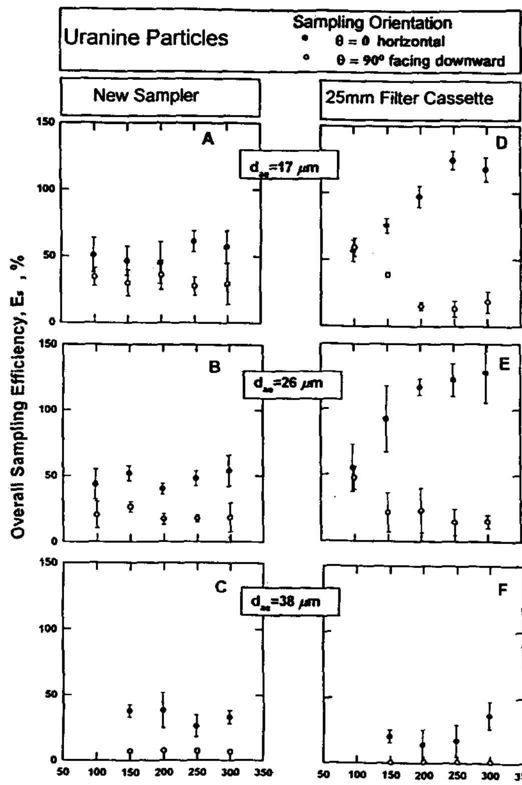

Fig. 4. Wind-tunnel data of the overall sampling efficiencies for the new sampler and the closed-face 25 mm filter cassette.

stains on a fibrous filter pad, lack of staining confirmed that the particles were fully solidified. The solid particles were sized under an opticle microscope using a Porton graticule. The upstream aerosol concentration, C_o, was determined with an isokinetic sharp-edged tubular sampler connected to a single particle optical counter (Model No. 245, Royco Instruments Inc., Menlo Park, California). The number of particles determined by the optical counter was corrected for gravitational settling in the isokinetic sampler using the equation for the laminar flow in a straight horizontal tube with a circular cross section (Brockmann, 1993).

The new sampler and the 25 mm filter cassette were mounted in the test section at the same height as the isokinetic sampler. The aerosol concentrations in the wind tunnel were checked before and after sample collection. The particle concentration in the wind tunnel was stable with variations no greater than $\pm 15\%$. Triplicate samples were collected for wind velocities ranging from 100 to 300 cm s^{-1} and the flow rate in the samplers was maintained at $2 \ell \min^{-1}$ throughout the experiments. The particles were collected in the samplers on polyvinyl chloride filters and were analyzed by means of a fluorometer (Model 110, Turner Associates, Palo Alto, California). The sampled aerosol concentrations, C_s, were obtained for both samplers by dividing the number of collected particles by the sampled air volume. Concentrations C_o and C_s, and equation (1) were used to calculate the overall sampling efficiencies.

Results and discussion

The sampling efficiency data for both samplers, tested at $\theta = 0$ and 90°, are shown in Fig. 4. The vertical bars indicate the standard deviation of the overall sampling efficiency to the mean of each set of results.

For a wind velocity range of 100–300 cm s^{-1} and a particle size of $d_{ae} = 17\ \mu m$, the average overall sampling efficiency of the new sampler is 52% for isoaxial and 31% for 90° sampling, Fig. 4A. For the same sampling conditions and $d_{ae} = 26$ and 38 μm, the respective averages are 47% and 20% (Fig. 4B), and 34% and 7% (Fig. 4C). There is no statically significant change (at the 95% confidence level) in sampling efficiency as a function of wind velocity. The overall sampling efficiency for the larger particles ($d_{ae} = 38\ \mu m$) could not be determined at the lowest wind velocity of 100 cm s^{-1} because of excessive gravitational losses in the reference sampler. Although the new sampler shows a decrease in overall sampling efficiency with increasing particle size and sampling angle, the overall sampling efficiency remains essentially constant over the entire range of wind velocities for a given particle size and sampler orientation.

In contrast, up to 2- to 3-fold increases or decreases have been recorded with the 25 mm closed-face filter cassette when exposed to the same range of wind conditions, Figs 4D–F. As seen in Figs 4D and E, this sampler is highly dependent on sampling orientation and wind velocity and may over-sample in the isoaxial position. Similar variations in sampling efficiency of this sampler have been demonstrated by Fairchild *et al.* (1980).

MICROSCOPIC ANALYSIS OF FILTER DEPOSIT

Method

To study the distribution of large particles over the filter surface, samples were collected using the horizontal high-velocity aerosol wind tunnel. Uranine particles of $d_{ae} = 17\ \mu m$ were generated, and two samples each were taken with the new sampler and the 25 mm filter cassette at three different sampler orientations: $\theta = 0$, downward at $\theta = 45°$ and downward at $\theta = 90°$. The wind velocity was constant at 250 cm s^{-1}. The collected samples were mounted on microscopic slides by dissolving the filter using acetone vapor. The particles were counted under a bright-field light microscope with a computer-controlled stage so that specific coordinates could be chosen on the filter surface. The area of each microscope field was calculated to be 0.0404 cm^2. The particles were counted in four diametric directions. Each diameter was divided into 11 sections and particles were counted in the center of each section. The section near the edge of the filter was not taken into consideration because of particle losses near the filter edge. Two counts were recorded for each field. A single mean and its standard deviation were determined for all data with each of the two samplers oriented in one of the three positions.

Results and discussion

Table 1 shows the relative standard deviations in count variation across the filters measured with the new sampler and the closed-face 25 mm filter cassette under limited conditions. It is seen that for isoaxial orientation the uniformity of filter deposition for the new sampler is more than twice that for the 25 mm filter cassette. The difference measured for the 45° orientation is not so significant but still indicates a preference for using the new device to obtain better filter deposit uniformity. No notable difference was found for the 90° orientation.

Table 1. Measured relative standard deviation (%) of particle count on the filter surface

Sampler	$\Theta = 0°$[a]	$\Theta = 45°$[a]	$\Theta = 90°$[a]
New[b]	19.2	19.7	33.9
Filter cassette[b, c]	44.6	28.2	33.6

[a] $\Theta = 0°$ (isoaxial), 45° (facing downward), 90° (facing downward).

[b] Closed-face 25 mm cassette.

[c] Tested with uranine particles of $d_{ae} = 17\ \mu m$ at $U_w = 250$ cm s^{-1}.

For comparison, the relative standard deviation assuming Poisson statistic (absolute standard deviation = square root of count) was also calculated. For the new sampler, the relative standard deviation due to Poisson count statistics alone was found to be 22.5% at $\theta = 0$, 17.7% at 45°, and 29.7% at 90°. These values of the Poisson count component of variability are approximately the same as the corresponding measured variabilities presented in Table 1. Thus, little of the measured variability in the new sampler is due to non-uniform deposits. For the filter cassette, the Poisson deviation was found to be 10.1% at $\theta = 0$, 10.9% at 45°, and 27.8% at 90°. The larger measured variabilities at 0° and 45° (44.6% and 28.2%, respectively) indicate that the greater percentage of these variability levels is due to non-uniform particle deposition on the filter. For both sampler at 90°, the low sampler loading contributed to high Poisson variability (29.7% for the new sampler and 27.8 for the filter cassette). In this case, it is difficult to make judgment on the sample uniformity due to inadequate statistics. However, in the 90° case for the new sampler, the surface density of deposited particles was observed to be higher on the upstream side of the filter.

The distribution of particles on the filter of the 25 mm filter cassette is non-uniform for all three orientations tested. For isoaxial sampling the collection of particles was highest in the center region, while for non-isoaxial sampling the distribution was highly variable across the filter surface. Baron *et al.* (1994) have shown that even when the 25 mm cassette is open-faced, large variations in filter deposit can occur under non-isoaxial sampling conditions.

CONCLUSIONS

Because the wind conditions do not remain constant in occupational and ambient air environments, sampling bias due to changing wind conditions should be minimal when sampling aerosols from such environments. Performance evaluations of the frequently used 25 mm closed-face cassette indicate a strong sampling efficiency dependence on wind magnitude and direction. By comparison, the experimental data collected with the new sampler indicate virtually no wind velocity dependence and much less wind direction dependence. The design of the new sampler is based on the aerodynamic quality of a bluff body which allows smooth flow over its surface in a fast moving wind. This flow pattern was confirmed visually using smoke stream tests. The pore diameter of the spherical shell can be used as the particle size limiting factor. An advantage of the shell is its ability to exclude particles that are approximately equal to or larger than its orifice size. Measurements of the filter deposits indicate that this inlet yields improved uniformity in particle distribution, an advantage when the filter is evaluated by a particle counting method.

Further work is required to investigate the performance of the new sampler under a wider range of sampling conditions and for various types of particles and particle sizes. The sampling efficiency may be adjusted to meet new sampler standards by choosing a different pore size, pore distribution, flow rate, and subtended angle.

Disclaimer—Mention of product or company name does not constitute endorsement by the Centers for Disease Control and Prevention.

REFERENCES

American Conference of Governmental Industrial Hygienists (1993) Threshold limit values for chemical substances and physical agents and biological exposure indices (1993–1994). ACGIH, 6500 Glenway Ave., Bldg D-7, Cincinnati, Ohio, U.S.A.

Badzioch S. (1959) Collection of gas-borne dust particles by means of an aspirated sampling nozzle. *Br. J. appl. Phys.* **10,** 26–32.

Baron P. A. and Deye G. J. (1990) Electrostatic effects in asbestos sampling—I. Experimental measurements. *Am. Ind. Hyg. Assoc. J.* **51,** 51–62.

Baron P. A., Chen C. C., Hemenway D. R. and O'Shaughnessy P. (1994) Nonuniform flow in inlets: the effect of filter deposits in the fiber sampling cassette. *Am. Ind. Hyg. Assoc. J.* **55,** 722–732.

Beaulieu H. J., Fidino A. V., Arlington K. L. B. and Buchan R. M. (1980) A comparison of aerosol sampling techiques: "Open" versus "Closed-Face" filter cassettes. *Am. Ind. Hyg. Assoc. J.* **41,** 758–765.

Belyaev S. P. and Levin L. M. (1972) Investigation of aerosol aspiration by photographing particle tracks under flash illumination. *J. Aerosol Sci.* **3,** 127–140.

Belyaev S. P. and Levin L. M. (1974) Techniques for collection of representative aerosol samples. *J. Aerosol Sci.* **5,** 325–338.

Berglund R. N. and Liu B. Y. H. (1973) Generation of monodisperse aerosol standards. *Environ. Sci. Technol.* **7,** 147–153.

Botham R. A., Hughson G. W., Vincent J. W. and Mark D. (1991) The development of a test system for investigating the performances of personal aerosol samplers under actual workplace conditions. *Am. Ind. Hyg. Assoc. J.* **52,** 423–427.

Brockmann J. E. (1993) Sampling and transport of aerosols. In *Aerosol Measurement: Principles, Techniques and Applications* (edited by Willeke K. and Baron P. A.). Van Nostrand Reinhold, New York.

Buchan R. M., Soderholm S. C. and Tillery M. I. (1986) Aerosol sampling efficiency of 37 mm filter cassettes. *Am. Ind. Hyg. Assoc. J.* **47,** 825–831.

Dunnet S. J. and Ingham D. B. (1988) An empirical model for aspiration efficiencies of blunt aerosol samplers oriented at an angle to the oncoming flow. *Aerosol Sci. Technol.* **8,** 245–264.

Fairchild C. I., Tillery M. I., Smith J. P. and Valdez F. O. (1980) Collection efficiency of field sampling cassettes. Report LA-8640-MS, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, U.S.A.

Grinshpun S., Willeke K. and Kalatoor S. (1993) A general equation for aerosol aspiration by thin-walled sampling probes in calm and moving air. *Atmospheric Environment* **27,** 1459–1470. Corrigendum (1994) *Atmospheric Environment* **28,** 375.

Hangal S. and Willeke K. (1990a) Aspiration efficiency: Unified model for all forward sampling angles. *Environ. Sci. Technol.* **24,** 688–691.

Hangal S. and Willeke K. (1990b) Overall efficiency of tubular inlets sampling at 0°–90° from horizontal aerosol flows. *Atmospheric Environment* **24**, 2379–2386.

International Standards Organization (1983) Air quality — Particle size fraction definitions for health-related sampling. Technical Report ISO/TR/7708-1983, ISO, Geneva, Switzerland.

Kucharski R. (1980) A personal dust sampler simulating variable human lung fraction. *Br. J. Ind. Med.* **37**, 194–196.

Mark D. (1990) The use of dust-collecting cassettes in dust samplers. *Ann. Occup. Hyg. J.* **34**, 281–291.

Mark D., Vincent J. H., Gibson H. and Lynch G. (1985) A new static sampler for airborne total dust in workplaces. *Am. Ind. Hyg. Assoc. J.* **46**, 127–133.

Mark D. and Vincent J. H. (1986) A new personal sampler for airborne total dust in workplaces. *Ann. Occup. Hyg.* **30**, 89–102.

Ogden T. L. and Birkett J. L. (1978) An inhalable dust sampler for measuring the hazard from total airborne particulate. *Ann. Occup. Hyg.* **21**, 41–50.

Ogden T. L. and Wood J. D. (1975) Effects of wind on the dust and benzene-soluble matter captured by a small sampler. *Ann. Occup. Hyg.* **17**, 187–195.

Okazaki K., Wiener R. W. and Willeke K. (1987a) Isoaxial sampling: nondimensional representation of overall sampling efficiency. *Environ. Sci. Technol.* **21**, 178–182.

Okazaki K., Wiener R. W. and Willeke K. (1987b) Non-isoaxial aerosol sampling: mechanisms controlling the overall sampling efficiency. *Environ. Sci. Technol.* **21**, 183–187.

Soderholm S. (1993) Proposal for converting "Total" dust limits to inhalable and thoracic dust limits. *Appl. Occup. Environ. Hyg.* **8**, 453–457.

Tufto P. A. and Willeke K. (1982a) Dependence of particulate sampling efficiency on inlet orientation and flow velocity. *Am. Ind. Hyg. Assoc. J.* **43**, 436–442.

Tufto P. A. and Willeke K. (1982b) Dynamic evaluation of aerosol sampling inlets. *Environ. Sci. Technol.* **16**, 607–609.

Vanderpool R. W. and Rubow K. L. (1988) Generation of large, monodisperse calibration aerosols. *Aerosol Sci. Technol.* **9**, 65–69.

Vaughan N. P., Chalmers C. P. and Botham R. A. (1990) Field comparison of personal samplers for inhalable dust. *Ann. Occup. Hyg. J.* **34**, 553–573.

Vincent J. H. (1989) *Aerosol Sampling — Science and Practice.* Wiley, New York.

Whitby K. T. and Liu B. Y. H. (1968) Polystyrene aerosols — electrical and residue size distribution. *Atmospheric Environment* **2**, 103–116.

Wiener R. W., Okazaki K. and Willeke K. (1988) Influence of turbulence on aerosol sampling efficiency. *Atmospheric Environment* **22**, 917–928.

Willeke K. and Baron P. A. (1990) Sampling and interpretation errors in aerosol monitoring. *Am. Ind. Hyg. Assoc. J.* **51**, 160–168.

Willeke K. and Baron P. A. (1993) *Aerosol Measurement: Principles, Techniques and Applications.* Van Nostrand Reinhold, New York.

Xu M., Nematollahi M., Sextro R. G., Gadgil A. J. and Nazaroff W. W. (1994) Deposition of tobacco smoke particles in a low ventilation room. *Aerosol Sci. Technol.* **20**, 194–206.