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New experimental methods for the development and evaluation of aerosol samplers†

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An understanding of the scaling laws governing aerosol sampler performance leads to new options for testing aerosol samplers at small scale in a small laboratory wind tunnel. Two methods are described in this paper. The first involves an extension of what is referred to as the "conventional" approach, in which scaled aerosol sampler systems are tested in a small wind tunnel while exposed to relatively monodisperse aerosols. Such aerosols are collected by test and reference samplers respectively and assessed gravimetrically. The new studies were carried out for a modified, low flowrate version of the IOM personal inhalable aerosol sampler. It was shown that such experiments can be carried out with a very high level of repeatability, and this supported the general validity of the aerosol sampler scaling laws. The second method involves a novel testing system and protocol for evaluating the performances of aerosol samplers. Here, scaled aerosol samplers of interest are exposed to polydisperse aerosols, again in a small wind tunnel. In this instance, the sampled particles are counted and sized using a direct-reading aerodynamic particle sizer (the APS). A prototype automated aerosol sampler testing system based on this approach was built and evaluated in preliminary experiments to determine the performance of another modified version of the IOM personal inhalable aerosol sampler. The design of the new test system accounts for the complex fluid mechanical coupling that occurs near the sampler inlet involving the transition between the external flow outside the sampler and the internal airflow inside the sampler, leading in turn to uncontrolled particle losses. The problem was overcome by the insertion of porous plastic foam plugs, where the penetration characteristics are well understood, into the entries of both the test and the reference samplers. Preliminary experiments with this new system also supported the general validity of the aerosol sampler scaling laws. In addition, they demonstrated high potential that this approach may be applied in a standardised aerosol testing method and protocol.

1 Introduction

It has long been known that exposure to airborne particles—in the ambient outside air, indoor air and workplace air—may be associated with a wide range of possible health effects. Although over the years we have sought to minimise such health effects by the implementation of standards aimed at limiting exposure, there remain significant aerosol-related problems in environmental and occupational health. So the assessment of exposure to aerosols continues to be a priority for air monitoring.

Particle size-selective criteria for defining health-relevant fractions, based on knowledge of how particles enter the body through the nose and/or mouth during breathing and subsequently penetrate into the human respiratory tract, have been proposed by the International Standards Organisation (ISO), the American Conference of Governmental Industrial Hygienists (ACGIH) and the Comité Européen Normalisation (CEN). These have since been adopted by a number of national standards setting bodies. A full description is given in a monograph published recently by the ACGIH Air Sampling Procedures Committee.[1] The coarse *inhalable* fraction, representing everything that enters the body during breathing, is the most relevant to the research described in this paper. It is of the greatest general interest not least because it contains both the intermediate thoracic and the fine respirable fractions, and also because—for standards—it is widely being used to replace what environmental and occupational hygienists have previously referred to as "total aerosol". In the context of occupational hygiene, it has become the practice to sample for health-relevant aerosol fractions using small personal samplers, worn on the body by exposed workers. In this way, it is possible to infer that the sampler provides information specifically about the exposure of the wearer, as well as for other workers similarly exposed.

The search for samplers with performance matching the inhalable fraction began in the late 1970s and early 1980s,[2–5] and has continued to the present day as interest has grown in finding samplers capable of accurately collecting this fraction. More recent studies have been conducted, most notably the large collaborative European study reported by Kenny *et al.*[6] The common feature of all such studies is the fact that they were all carried out in wind tunnels large enough to accommodate life-size mannequins, on which the personal samplers of interest were mounted to simulate directly how they would perform when they were actually being worn by workers. In addition, the mannequins and samplers were exposed to quasi-monodisperse aerosols generated from narrowly-graded powders, dispersed as uniformly as possible throughout the wind tunnel working section, and the collected aerosol samples were analysed gravimetrically. However, such experiments are very difficult to set up, time consuming and—in turn—very expensive. So thoughts are now turned towards the development of standard procedures by which existing and new samplers can be characterised and evaluated according to some more convenient, yet consistent and well-defined, protocol.

Earlier research in our laboratory funded by the United States National Institute for Occupational Safety and Health (NIOSH) provided an initial scientific basis for the application

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of laboratory studies in small-scale wind tunnels in aerosol sampler research.[7,8] Notable outcomes were the identification of scaling laws by which such studies could be related to practical aerosol sampling under realistic conditions, and the introduction of direct-reading instrumentation for determining the aspiration efficiencies of aerosol samplers. Two new projects are under way, both resulting directly from that earlier work and also supported by NIOSH, aimed at the development of new test methods for characterising aerosol samplers along the desired lines indicated and also the development of new personal samplers for the inhalable aerosol fraction for use in occupational hygiene. This paper describes the new methods that have been developed during this body of work.

2 Theoretical basis

Aspiration efficiency (A) is the primary index describing the performance of an aerosol sampler. For practical purposes it is given by

$$A = c/c_0 \quad (1)$$

where c is the concentration of particles passing through the sampler entry and c_0 is the concentration of particles originally contained in the aspirated air volume. For sampling in the context of occupational or environmental health, this should match the inhalability criterion. Aspiration efficiency may be generally described as a function of several dimensionless parameters that relate to both fluid and particle motion near the sampler, thus

$$A = \mathrm{f}\,(St, R, r, \alpha, Re_\mathrm{f}, Re_\mathrm{p} \ldots\ldots) \quad (2)$$

where St is the Stokes' number embodying inertial effects (which, for most aerosol sampling situations, are usually assumed to be the predominant forces acting on the airborne particles, significantly outweighing gravity). In addition, R is the ratio of freestream velocity to the mean velocity of air passing through the plane of the orifice (U/U_s), r is the ratio of sampler entry orifice width to the sampler body (δ/D) and α is the orientation of the sampler with respect to the wind. Here, St is given by

$$St = d_\mathrm{ae}{}^2\, \rho^*\, U/18\, \eta\, \delta \quad (3)$$

where d_ae is the particle aerodynamic diameter, ρ^* the density of water and η the viscosity of air. Other parameters to be considered are the Reynolds number for the flow outside the sampler (Re_f) and the Reynolds number for the particle motion relative to the flow (Re_p). Still others may include dimensionless groups to account for the effects of freestream turbulence, or other relevant fluid mechanical effects. Each of these could be important under specific sets of conditions. Both Re_f and Re_p define the ratio of the magnitude of inertial forces in the main body of the flow to the magnitude of viscous forces close to the flow boundaries, macroscopically for the flow about the sampler and microscopically for the flow about the particle, respectively. Although Re_f has been included in some considerations of aerosol sampler scaling,[9] it is a fair assumption for the range of most conditions of aerosol sampling that it falls within the range where physical behaviour is not very sensitive to changes in Re_f. So it is reasonable to neglect it. Similarly, Re_p may be neglected over the range where particle motion relative to the air approximately follows Stokes' law. Furthermore, the small amount of empirical evidence that exists suggests that freestream turbulence has a relatively weak effect over the ranges of conditions envisaged for practical aerosol sampling.[10]

Strict application of eqn. (2) severely constrains the practicability of scaling aerosol samplers along the lines described in the present research. But the removal of the need to scale with respect to Re_f and Re_p, as well as the other dimensionless parameters suggested, greatly increases our practical options. For a given sampler geometry and orientation with respect to the wind (including orientation averaged over 360°), the problem is then reduced to

$$A = \mathrm{f}\,(St, R, r) \quad (4)$$

As already mentioned, scaling aerosol sampling systems between large and small is an important theme in the body of work that has been developed. Describing A in terms of dimensionless groups as shown in eqn. (4) allows scaling according to basic engineering principles. This means that, regardless of the physical size of the sampler in question, the air velocities in the system of interest, and the size of the particles being aspirated, A should remain the same as long as St, R and r remain the same.

In the scenario described, the actual independent variables that are controlled are U, U_s, D, δ and particle size as represented by d_ae. In order to keep R constant, U and U_s must be scaled by the same factor (k_U) as that pertaining to the full-scale system. Likewise, to keep r constant, D and δ must be scaled by the corresponding factor k_D. The scaling factor for d_ae is then $k_{d\mathrm{ae}}$, where

$$k^2{}_{d\mathrm{ae}} = k_U \cdot k_D \quad (5)$$

This provides flexibility in designing a small-scale system that physically matches the full-scale system of interest. It is the primary basis for what is described below.

3 Primary facilities

The primary equipment for this work is the small open-loop wind tunnel shown in Fig. 1. It has a working cross-section of 30 cm × 30 cm, and air movement is driven by a tubular centrifugal fan located downstream of the working section. Air enters the working section from an inlet plenum containing a HEPA filter bank, a honeycomb screen and a 6.25 : 1 contraction to suppress the penetration of external large-scale air motions into the working section. After passing through the working section, the air regains static pressure as it passes through a diffuser, and is discharged through another HEPA filter bank.

The front part of the test chamber consists of a dispersion section, where mechanically-aerosolised powders are introduced (see below). In the experiments described in this paper, the aerosols were generated from such powders using a mechanical aerosol generator (Topas Model SAG 410, Topas GmbH, Dresden, Germany). The aerosols were injected into the airflow just upwind of a 15 cm × 15 cm mixing plate placed

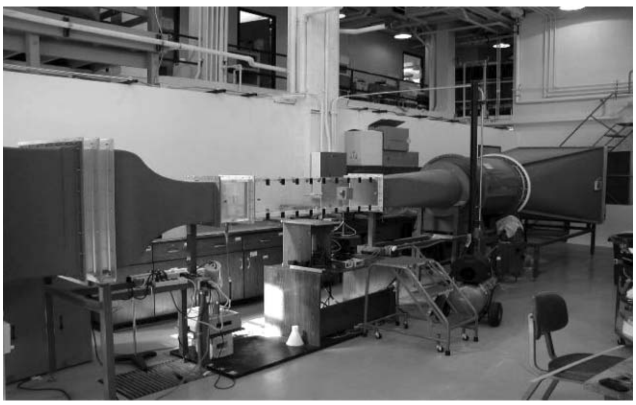

Fig. 1 Small wind tunnel used in the research described in this paper.

there to achieve uniform dispersal of the particles at the working section. The compressed air supply to the aerosol generator was of sufficient flow to provide an agglomerate-free aerosol. As a further measure to aid dispersion, the test powders were stored in a heated oven prior to use. During the experiments themselves, a 250 W spot lamp was used to maintain heat in the powder reservoir of the generator. Aerosols generated in this way were not neutralised, based on evidence that the influence of such effects on aspiration efficiency are weak in most cases.[11] However, as a precautionary measure, the dust generator, aerosol injection line and all sampling tubes were electrically grounded.

A square-mesh grid was located just downstream of the dispersion section to further facilitate mixing of the injected aerosol and also to establish well-defined turbulence in the test section. Here, for a bar width of 0.84 cm, turbulence intensities were 5% and 3.3% and turbulence length scales were 2 cm and 2.8 cm at the locations of the isokinetic and test probes, respectively.[12] These conditions prevailed throughout all the experiments described.

The important general question of wind tunnel blockage deserves comment. In the original studies in large wind tunnels, the geometrical blockage to the air flow presented by the bluff body of the full-scale model torsos was generally small, less than 5%. For corresponding studies in small wind tunnels, like the ones reported here, it is inevitable that such blockage will be higher. The dimensions of the largest such bluff body used in the current work (see below) were 12 cm × 12 cm × 6 cm (see below). When this bluff body was rotated slowly about a vertical axis in order to achieve the desired orientation-averaging, the resultant wind tunnel blockage varied between 8 and 16%. Although the resultant mean air velocity in the plane of the body would now be correspondingly higher (than in the undisturbed freestream), and may therefore influence the nature of the air and particle flows in the vicinity of the body, experience in our other research suggests that any resultant such effects are small for blockage fractions of the order of those indicated.[13,14] Meanwhile, the draft European standard for the assessment of the performance of workplace aerosol sampling instruments (prEN13205) requires that the wind tunnel blockage should not exceed 15%.[15] Overall, we are reassured that, for the present work, the wind blockage was small enough to (a) ensure that fluid mechanical effects would not be significant and (b) fall within the requirements of the most appropriate technical standard.

4 Testing and developing samplers by conventional methods

Approach

The first part of the research set out to develop new personal aerosol samplers for the inhalable aerosol fraction, using testing procedures analogous to those applied in the large wind tunnel studies of much of the previous reported work in this area. Such research, conducted in our small wind tunnel, therefore requires careful reference to the scaling laws described above.

The conventional approach involves the use of aerosols in a series of individual experiments such that the aspiration efficiency characteristics as functions of the various influential variables may be built up, one experimental run at a time. The approach itself requires the collection of aerosols of known particle size by both the sampler under test and a suitable reference sampler (usually a thin-walled sampling probe operated isokinetically), and determining the mass of aerosol material entering each. Aspiration efficiency is then calculated using eqn. (1). Reliable experimental protocols have been developed for this approach, and are widely used. The work carried out in this project not only satisfies the immediate need to aid in the development of new aerosol samplers but also provides a bridge to the search for new testing methods described in the second part of this paper.

Test samplers

The Institute of Occupational Medicine (IOM) personal inhalable aerosol sampler (SKC Ltd., Blandford Forum, Hants, UK) is widely regarded as an appropriate reference sampler for the inhalable aerosol fraction.[16] It is notable also for the fact that the use of the instrument requires analysis of the whole catch of particulate material—that is, everything that passes through the entry, including not only that which is collected on the filter but also that collected on the internal walls of the sampler's cassette. Thus aspiration efficiency is a direct index of the performance of the IOM sampler. The purpose of the experiments described in this paper was to examine whether a scaled version of the IOM tested in our small wind tunnel has performance that matches that of the full-scale version tested under life-sized conditions. Data for the latter are available from the previously published results of Mark and Vincent in 1986 and Kenny *et al.* in 1995 and 1997.[5,6,17] Based on the preceding discussion about scaling laws, Table 1 shows the experimental conditions for the full-scale experimental studies (subsets from the Mark and Vincent and the Kenny *et al.* data) alongside the corresponding scaled-down conditions suitable for testing in our small wind tunnel. Here, the width of the sampler body (D) is taken to be the width of the bluff body on which the sampler itself is mounted. So for the full-scale version D is the width of the body of the mannequin (approximately 300 mm), while for the small-scale version it is the width of a rectangular bluff body on which the sampler was mounted (120 mm).

Table 1 identifies a scaled-down version of the IOM sampler, with a smaller orifice diameter and a lower flowrate. To achieve the small geometry, the entry of the existing IOM sampler was modified simply by adding a face plate with the smaller orifice. The original and modified IOM sampler are shown in Fig. 2. The modified IOM is shown in Fig. 3 mounted centrally on the 120 mm bluff body in the manner it was tested in our experiments.

In both the full-scale experiments of Mark and Vincent and of Kenny *et al.*, as well as the present scaled experiments, the test sampler systems were rotated either incrementally or steadily about the vertical axis in order to achieve orientation averaging. One difference between the full-scale and small-scale experiments was the shape of the bluff body (though the size itself was also scaled) and the relative wind tunnel blockage (as already mentioned). For all the earlier Mark and Vincent experiments, the sampler had been mounted on the lapel of the mannequin. But in the 1995 Kenny report, some of the results are reported for the sampler mounted centrally on the torso of the mannequin. Since this is directly similar to the symmetrical configuration in our new scaled experiments, it is this subset that will be used here for comparison purposes. That said, it is

Table 1 Scaling relationships for full-scale studies and small-scale studies with the IOM sampler and modified IOM sampler respectively

	Full-scale (Mark and Vincent, 1986; Kenny *et al.*, 1997)	Small-scale (present work)
d_{ae}/μm	8–96	6–90
δ/mm	15	6
D/mm	300	120
U/m s^{-1}	1	1
Flowrate, Q/L min^{-1}	2	0.32
St	0.007–1.87	0.018–4.05
R	5.3	5.3
r	0.05	0.05

Fig. 2 IOM personal inhalable aerosol 2 L min^{-1} sampler (left) and the modified 0.3 L min^{-1} version (right).

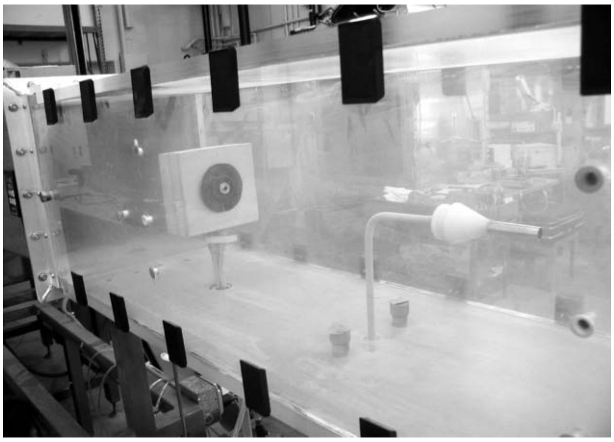

Fig. 3 Photograph of experimental set-up for determining the aspiration efficiency of the 0.3 L min^{-1} modified IOM sampler in the small wind tunnel by the conventional method.

noted from the cited study that positional effects associated with the placement of the sampler on the life-size torso were small.[6,17]

Experimental set-up and procedures

For these experiments, test aerosols were generated from narrowly-graded ('optical grade') powders of fused alumina (Washington Mills Electromineral Company, Niagara Falls, NY). Such powders have been widely used for aerosol studies since the 1980s,[18] and are considered to be approximately 'monodisperse' for the type of applications like those in this study. The particular powder grades used in this research (nominal Grades F1200, F600, F400, F320, F280 and F240) were identical to the ones originally used to produce calibrated aerosols as corresponding to mass median particle aerodynamic diameters (d_{ae}) of 6, 18, 34, 58, 74 and 90 μm respectively. Other workers have also used these same grades from the same supplier in their own research and confirm that their more recent calibrations do not differ significantly from the original ones.

As previously mentioned, the test sampler was mounted centrally on a rectangular block of width 120 mm and thickness 60 mm. Because of the size of the sampler body relative to the bluff body (which was more pronounced than for the actual sampler mounted on the full-size mannequin), the sampler was recessed into the bluff body so that it did not project out significantly beyond the bluff body surface. The reference sampler was a 10 mm diameter thin-walled probe located centrally in the wind tunnel a distance 0.5 m upstream of the test sampler and 0.7 m downwind of the turbulence-generating grid at the entrance to the working section. It contained a 25-mm filter holder containing a glass fibre filter. A cone was placed around the filter holder to minimise the effect of aerodynamic blockage on the aspiration characteristic of the thin-walled probe. The complete experimental set-up is shown in Fig. 3. The whole aspirated catch of particulate material was analysed. In order to recover the wall deposits, two 55 mm glass fiber filters were pushed through the tube onto a third filter. The three filters were weighed together. The sum of the wall deposit obtained in this way and the mass collected on the primary 25 mm filter were used to determine the reference aerosol concentration. All filters, as well as the cassettes from the test samplers were weighed using an electronic balance (Model MC201S; Sartorius Corporation, Edgewood, NY) after appropriate conditioning.

For each experimental sampling run, this system yielded two test samples, the single upstream one providing the reference concentration and the downstream one providing the concentration aspirated by the test sampler. Before these quantities were applied in eqn. (1) for the calculation of aspiration efficiency, A, the reference concentration was adjusted for the change in freestream aerosol concentration between the reference and test points in the absence of the test sampler system (as described in detail elsewhere[19]).

Preliminary results and discussion

Preliminary results from this study are presented in this paper. Results for the aspiration efficiency of the small-scale, low-flowrate version of the IOM sampler are shown in Fig. 4. Here the results are shown first in the familiar form of A plotted against d_{ae} (Fig. 4a), and then in the form of A *versus* St, which is more appropriate for scaling purposes (Fig. 4b). Here, R and r had been set at the same values as those pertaining to the earlier full-scale experiments of Mark and Vincent and of Kenny *et al.* The first thing to note is that the repeatability of the new experiments was very good indeed. Based on eqn. (4), there is a reasonable expectation that the two sets of data should be in agreement. The fact that they are reasonably close is encouraging. However there does appear to be a small bias, with the modified IOM sampler in the scaled experiments slightly over-sampling in relation to the corresponding full-scale experiments. At this stage there is no obvious explanation for this bias, and it will be examined in further detail in subsequent experiments.

5 A new rapid method for testing and developing samplers

Approach

The second part of the research set out to develop new methods for the rapid testing of personal (and other) aerosol samplers, again using the small wind tunnel described earlier, and by reference to the scaling laws that already have been outlined. The new approach follows the one first indicated in our earlier reports.[7,8] It is based on the application of the direct-reading Aerodynamic Particle Sizer (APS) (Model 3320, TSI, Inc., St. Paul, MN) in a manner similar to the way it has been used for the rapid experimental determination of aerosol penetration through cyclones and other particle size-selective media. By using polydisperse test aerosol, this approach allows results from a wide range of particle sizes to be obtained within a single experimental run. In this way, there is the potential for considerable savings in time and cost. Although the APS counts and sizes particles with d_{ae} only up to about 20 μm, application of the scaling laws referred to above permits

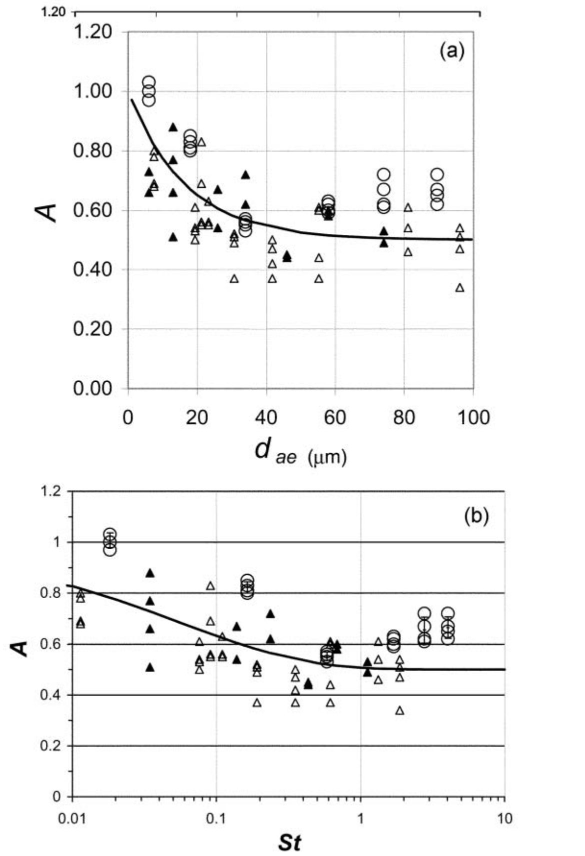

Fig. 4 Fig. 4 a, Experimental results for the aspiration efficiency of the modified 0.3 L min^{-1} aerosol sampler obtained using the experimental set-up shown in Fig. 3, with raw data for A plotted in terms of particle aerodynamic diameter, d_{ae}. These were obtained using the experimental set-up shown in Fig. 3, and for the scaled conditions, R = 5.3 and r = 0.05 (open circles). Also shown are: solid line—inhalability curve; closed triangles—data from Mark and Vincent (1986); open triangles—data from Kenny *et al.* (1997). b, Same experimental results as in a, for the aspiration efficiency of the modified 0.3 L min^{-1} aerosol sampler, plotted in terms of A *versus* St. These were obtained using the experimental set-up shown in Fig. 3, all for the same scaled conditions, R = 5.3 and r = 0.05 (open circles, with error bars reflecting the standard deviation from repeat runs). Also shown are: solid line—inhalability curve; closed triangles—data from Mark and Vincent (1986); open triangles—data from Kenny *et al.* (1997).

identification of experimental conditions, including particle size range, that can be related back to realistic conditions at full-scale.

The new approach is based on the system shown schematically in Fig. 5. It requires measurement of the counts of particles of given aerodynamic diameter reaching the APS in each of the two sampling lines shown, the first containing the reference sampler where the aspiration characteristics are known and the second containing the actual sampling system of interest where the aspiration characteristics are not known. The air volumetric flowrate is the same in each line. By repeated counts in each line, by switching backwards and forwards from one to the other, comparison of the counts obtained for each line will provide information from which to determine the aspiration efficiency of the sampler of interest.

The entry loss problem

The practical implementation of the approach described is influenced and modified by the growing awareness from our own earlier work for both thin-walled and blunt sampling probes,[20,21] and that of Willeke and his co-workers for thin-walled probes,[22,23] that the coupling between the external air flow and the internal air flow just inside the sampler entry is extremely complicated and needs to be taken into account. This 'entry effect' relates to the fact that the external air flow undergoes a sharp transition during entry into the sampler, including boundary layer effects and—under certain conditions—flow separation and instability. By way of illustration, Fig. 6 illustrates the *vena contracta* that results from the aforementioned flow separation for the simple case of the thin-walled sampling probe. More generally, the actual details of such flow will be highly dependent R, r and α. So too will be particle losses by deposition in that region, and these have been shown to be considerable.[20,21] Although an empirical model has been developed for such particle deposition for a thin-walled sampling probe,[20] we consider that there is no prospect of extending this in order to obtain a general model that may be broadly applied to 'real-world' aerosol samplers like those used in practical occupational and environmental hygiene.

With the above in mind, the application of a direct-reading instrument along the lines indicated is seen to be problematical. This is because, although an instrument such as the APS can indeed accurately count and size particles that reach its sensing zone, it cannot take account of all the losses that occur elsewhere in the sampling line. The problem is identified more clearly by reference to Fig. 5 and the following equations, thus

$$_{\mathrm{T}}E = \frac{_{\mathrm{T}}c_{\mathrm{APS}}}{c_0} = \frac{_{\mathrm{T}}c_{\mathrm{APS}}}{_{\mathrm{T}}c_{\mathrm{e}}} \times \frac{_{\mathrm{T}}c_{\mathrm{e}}}{_{\mathrm{T}}c} \times \frac{_{\mathrm{T}}c}{c_0} = {_{\mathrm{T}}P_{\mathrm{tube}}} \times {_{\mathrm{T}}P_{\mathrm{entry}}} \times {_{\mathrm{T}}A} \quad (6)$$

$$_{\mathrm{R}}E = \frac{_{\mathrm{R}}c_{\mathrm{APS}}}{c_0} = \frac{_{\mathrm{R}}c_{\mathrm{APS}}}{_{\mathrm{R}}c_{\mathrm{e}}} \times \frac{_{\mathrm{R}}c_{\mathrm{e}}}{_{\mathrm{R}}c} \times \frac{_{\mathrm{R}}c}{c_0} = {_{\mathrm{R}}P_{\mathrm{tube}}} \times {_{\mathrm{R}}P_{\mathrm{entry}}} \times {_{\mathrm{R}}A} \quad (7)$$

Here, P_{entry} is the penetration efficiency for particles passing through the flow transition region near the inlet and P_{tube} the penetration efficiency for particles passing through the length of the tube between the entry and the APS. The subscripts 'R' and 'T' refer to the reference and test samplers respectively. The

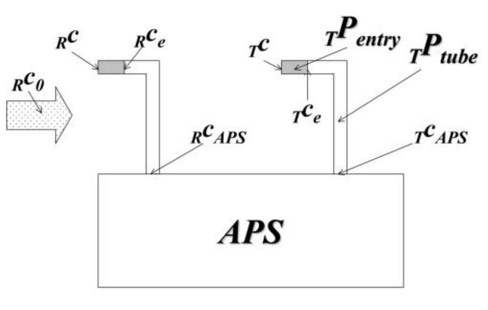

Fig. 5 Schematic of the proposed new sampler testing system, showing the aerosol concentrations at various stages in each sampling line, and identifying the penetration efficiency of both the entry section and the sampling tube.

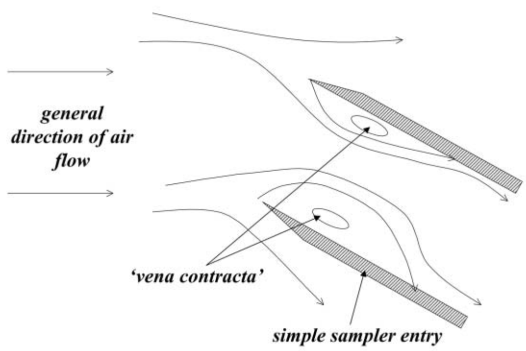

Fig. 6 Schematic to illustrate the nature of the inlet problem for a simple thin-walled sampling probe placed at an angle to the freestream.

aerosol concentrations referred to at the various points within the system are as indicated in Fig. 5. In eqn. (6) and (7), it is seen that the APS counts can be used to determine aspiration efficiency of the test sampler (${}_{\mathrm{T}}A$) only if all the other terms are known or can be eliminated. The former can be achieved for ${}_{\mathrm{R}}A$ by the choice of an appropriate reference sampler—for example, a thin-walled sampling tube facing the wind, whose aspiration efficiency is well-known from theory. The latter can be achieved for P_{tube} by ensuring that the physical dimensions of the tube between the entry and the APS are identical for each sampling line, so that ${}_{\mathrm{R}}P_{\mathrm{tube}}$ and ${}_{\mathrm{T}}P_{\mathrm{tube}}$ cancel. However, the same cannot be achieved for P_{entry} because, as already stated, this cannot be calculated. The solution we have adopted for the latter involves making artificial modifications of the entries of both the reference and the test samplers so that P_{entry} can be predicted after all.

Application of foam filtration media

Porous plastic foam media have been considered in recent years as possible pre-selectors for aerosol samplers, based on their well-behaved filtration characteristics. Vincent *et al.*[24] collected available experimental data for the efficiency of aerosol penetration through a cylindrical plug of such media (${}_{\mathrm{F}}P$), and used them to obtain

$$\ln({}_{\mathrm{F}}P) = -(t/d_{\mathrm{f}})\{54.86\,{}_{\mathrm{F}}St^{2.382} + 38.91\,{}_{F}N_g^{\ 0.880}\}10^{-3} \quad (8)$$

where ${}_{\mathrm{F}}St$ is the Stokes' number for particle inertial motion near the microscopic elements of the porous structure of the foam media and ${}_{\mathrm{F}}N_g$ is the corresponding dimensionless parameter defining the role of gravity. These parameters are given by

$${}_{\mathrm{F}}St = d_{\mathrm{ae}}^{\ 2}\ \rho^*\ U_{\mathrm{foam}}/18\ \eta\ d_{\mathrm{f}} \quad (9)$$

$${}_{\mathrm{F}}N_g = d_{\mathrm{ae}}^{\ 2}\ \rho^*\ g/18\ \eta\ U_{\mathrm{foam}} \quad (10)$$

in which U_{foam} is the air velocity as it enters the foam plug, and d_{f} is the width of the microscopic elements that make up the foam media. Finally, in eqn. (8), t is the length of the cylindrical foam plug, and all variables are expressed in SI units. The foams are conventionally classed by nominal porosity in 'ppi' or 'pores per linear inch'. Eqn. (8) has since been independently tested against a significant amount of new data from two different laboratories and was confirmed as providing a good prediction of foam penetration.[25] It therefore provides a useful basis for designing foam plugs with well-defined, calculable, penetration characteristics.

The object in the proposed new system is that, by placing plugs of such porous plastic foam media immediately inside the entries of both the reference and the test samplers, the flow in the entry is now determined entirely by the flow through the foam media, irrespective of the orientation of the sampler. In this way, therefore, the flow transition and disturbance described earlier are suppressed. Now, based on eqn. (8), ${}_{\mathrm{R}}P_{\mathrm{entry}}$ and ${}_{\mathrm{T}}P_{\mathrm{entry}}$ may both be calculated. The practical problem that remains, therefore, is to ensure that the foam plugs are sufficiently ***in***efficient across the whole range of particle sizes of interest that enough particles reach the sensing zone of the APS for accurate particle counting.

Experimental set-up and procedures

For these experiments, a polydisperse test aerosol was generated from powders of glass beads in which 80% of the mass comprised particles of diameter between 13 and 44 µm (325 mesh, Class IV GL-0191, MO-SCI Corp., Rolla, MO). Unlike the experiments described earlier in this paper, the temporal stability of the aerosol concentration is now crucial since the APS samples are not taken simultaneously but, rather, alternating between the reference and sampler. Using the Topas generator described earlier, the flow of particulates to the point of aerosolisation prior to injection into the wind tunnel is metered accurately by means of a small conveyor belt. This provides good stability that, averaged over time, the aerosol generation rate is sufficiently constant for the present experiments. The actual delivery rate was adjusted to provide aerosol concentration in the working section high enough to provide good particle counts across the range of particle sizes of interest yet not so high as to cause coincidence counts in the APS. With this in mind, the overall particle count concentration at the APS was maintained within the range from 50 to 400 particles cm^{-3}.

The porous plastic foam media were obtained commercially in sheets 5 mm thick (Foam Engineers Ltd., Buckinghamshire, UK), one with 20 ppi and the other with 30 ppi. For each foam grade a pair of identical cylindrical plugs was carefully cut, one for the test sampler and the other for the reference sampler, with diameter sufficient to ensure a snug fit in each of the sampler inlets. Prior to each experiment, the foam plugs for both the test and reference samplers were immersed in a 10% mixture of petroleum jelly in xylene and dried to leave a uniform greased surface that minimised re-entrainment of deposited particles. Preliminary experiments confirmed that greasing the foams in this way did indeed prevent such re-entrainment.

The APS Model 3320 is a direct reading instrument that sizes individual particles based on their time-of-flight in a changing flow field and counts them based on light scattering. In this way, individual particle counts are placed into 52 electronic bins representing narrow particle size bands in the range of d_{ae} from approximately 0.5 to 20 µm. In our experiments, data were acquired using Aerosol Instrument Manager software (Version 1.6, TSI, Inc., St. Paul, MN) on a laptop computer. Software was also compiled to control the collection of samples alternately and repeatedly through each of the sampling lines indicated in Fig. 5. For each individual run, five such samples were taken in the sequence 'R'–'T'–'R'–'T'–'R'. Sample duration was adjusted to obtain sufficient total counts (> 100) in each channel; typically 90 to 120 s. Data records from each such run were exported to a program (Microsoft Excel) that compared particle counts for the sampler to the reference and computed the average efficiency. The result was the ratio ${}_{\mathrm{R}}E/{}_{\mathrm{T}}E$ from which, using eqn. (6) and (7), along with the known aspiration efficiency of the reference sampler (${}_{\mathrm{R}}A$) and the known penetrations through the foam plugs placed inside the entry of each sampler (${}_{\mathrm{R}}P_{\mathrm{entry}}$ and ${}_{\mathrm{T}}P_{\mathrm{entry}}$, respectively), the desired aspiration efficiency of the test sampler (${}_{\mathrm{T}}A$) could be obtained.

Prototype aerosol sampler testing system

Based on the preceding individual experimental components, the complete prototype aerosol sampler testing system is as shown in Fig. 7 and 8. The central part of this facility contains the reference and test samplers, the sampling lines, the APS and its associated controlling and data acquisition systems, and the switching arrangement that permits sampling alternately through the reference and test sampler lines.

A major technical aim was to ensure that each sampling line was identical to the other. The majority of the system was constructed of ½ in. OD stainless steel tubing. Since sudden restrictions or large cavities in the tubing may contribute significantly to particle losses, switching was achieved using pinch valves on short sections of the sampling lines made up from ½ in. ID silicone tubing. Such tubing is highly flexible and the interior diameter of the system therefore remains nearly

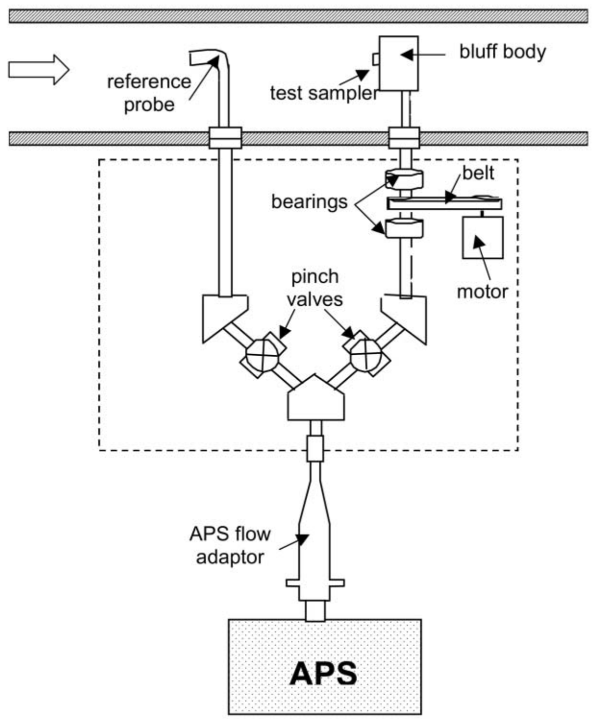

Fig. 7 Schematic of the prototype new aerosol sampling test system (seen from the front).

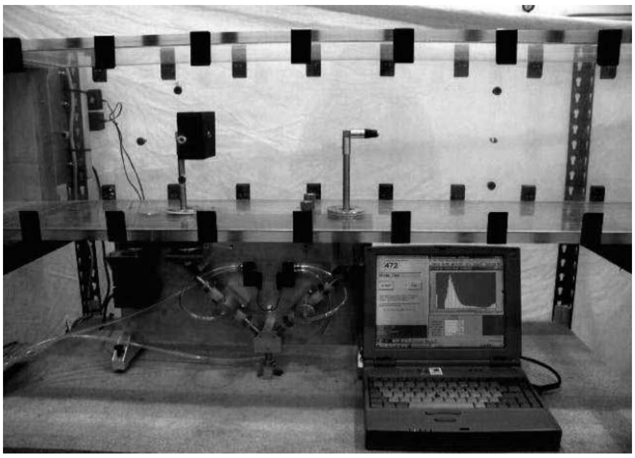

Fig. 8 Photograph of the prototype new aerosol sampler test system (seen from the back—*cf.* Fig. 7).

constant when the valve is open, even after repeated cycles of opening and closing. That notwithstanding, however, in actual use, the short segments of silicone tubing are changed frequently to minimise effects associated with tube deformation after many repeated cycles of valve closure. In the design of the Y-connection, where the reference and sampler lines come together, two competing factors had to be balanced. On the one hand it was desirable to minimise particle losses between the foam plug and the APS, in which case the connecting tubing should be kept as short as possible. However, to avoid excessive losses due to gravity, we set out to position the tubes as close to vertical as possible. The most appropriate compromise was to have the two arms of the Y-connection placed at 45° angles to the horizontal. In this new system, the pinch valves are driven by solenoid-driven, compressed-air actuators. Switching is controlled by a Visual Basic program installed on the laptop computer, through a digital I/O PCMCIA Card (Keithley Instruments Inc., Cleveland, OH, USA), and actuations of the valves are timed so that approximately 15 s are allowed to elapse, before and after each APS sample is taken, before the valve closes. This time delay allows the sampling lines to be completely flushed and equilibrate with the new incoming sample.

The APS requires a constant flowrate of 5 L min^{-1}, provided by an internal pump. In order for the test and reference samplers to sample at flowrates larger or smaller than 5 L min^{-1}, a tapered flow adapter was designed with additional ports to either add clean air or remove particle-laden air from the system. This was designed so that such addition or subtraction of air did not distort the flow field at the APS entry.[26]

Preliminary results and discussion

Preliminary experiments were conducted using the new prototype aerosol sampler testing system. The aim was to examine the basic feasibility of using the system for sampler testing along the lines proposed. For these experiments, scaling did not exactly match the earlier full-scale experiments or even our own other small-scale experiments (presented in Fig. 4). This was due to the initial desire to make the two sampling lines identical, including the foam plugs in each arm, such that the P_{entry} and P_{tube}-values would cancel directly—see eqn. (6) and (7). This constraint will be eased in the larger body of future work with the new system by careful consideration of the geometry of the test sampler and reference sampler respectively in order to avoid inconsistencies between the two. But for the present pilot studies the internal diameters of the both the reference sampler and the modified IOM sampler were made identical at δ = 11 mm (a standard internal diameter of the ½ in. OD stainless tube used throughout the prototype system). Here, therefore, the dimensions of the foam inserts for both samplers were 11 mm (diameter) and 5 mm (thickness), from which, if desired and for a given flowrate, the aerosol penetration efficiencies P_{entry} and P_{tube} could be estimated quite accurately from the model expressed in eqn. (8). The modified IOM was mounted on a rectangular bluff body of width (D) 8.8 cm (*cf.* 12 cm for the bluff body used in the experiments described in the first part of the paper). For these experiments, therefore, we held R = 5.3 (same as for the earlier studies) and r = 0.125 (larger than the earlier studies). To achieve this, the windspeed (U) was held at 0.73 m s^{-1} in order to achieve scaling with respect to the full-scale data that had been obtained for 1 m s^{-1}; also the flowrate for the test and reference samplers was 0.79 L min^{-1}.

The results are shown in Fig. 9, alongside the previous experimental data of Mark and Vincent and Kenny *et al.* for R = 5.3 and r = 0.05, also the same as plotted in Fig. 4. The new data are based on three replicate runs for each of the two foams used, following the sequence indicated above, and the error bars shown represent standard deviations from the mean. Here, it is seen that a small bias exists between the results for the two foams for small values of St, and this will be explored in more extensive future studies. In addition, the variability is generally greater than for the corresponding results obtained by the conventional approach (see Fig. 4). This is the result of the intrinsic variability that exists in the experimental method, most notably as influenced by the short-term changes in aerosol concentration level as the APS is switched between the reference and test samplers. Although the level of such variability is acceptable, future work will also include refinements of the experimental system and protocol to decrease this source of scatter.

Despite these small departures, the limited results in this preliminary demonstration compare very well with the earlier published data when plotted in dimensionless form against St for fixed R. However, it is noted that the range of St using the new method was smaller in these experiments than for the conventional method (see Fig. 4). This is the result of constraints imposed by the choice of porous foam media that

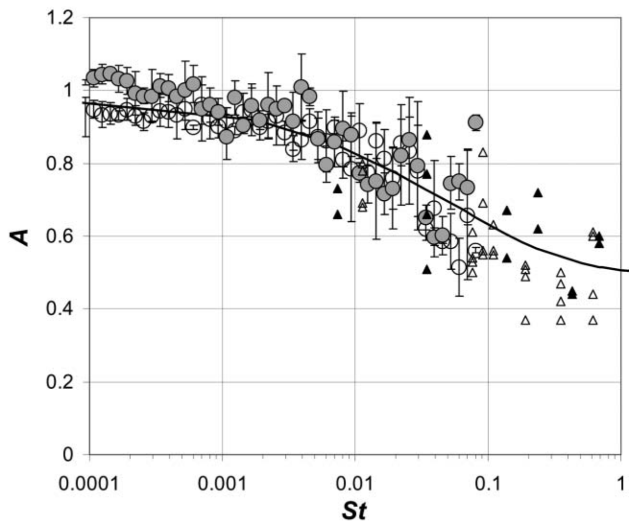

Fig. 9 Preliminary results obtained using the prototype new aerosol sampler test system. The grey circles show experimental results for the modified 11 mm orifice, 0.8 L min^{-1}, IOM sampler (same as for Fig. 4), for $R = 5.3$ and $r = 0.125$, and for 20 ppi foam. The open circles are identical conditions with the use of a 30 ppi foam. The error bars represent the standard deviation from the mean for 3 replicate runs. Also shown are: solid line—inhalability curve; closed triangles—data from Mark and Vincent (1986); open triangles—data from Kenny *et al.* (1997), all for $R = 5.3$ and $r = 0.05$.

achieve the desired elimination of the flow transition problem previously discussed and yet still allow sufficient particles to penetrate in order that they may be counted by the APS.

The fact that agreement is good, even though r was not held strictly constant, is not surprising because, as shown in other work in our laboratory (to be published),[27] the aspiration efficiency of blunt samplers is not strongly dependent on r provided that δ is sufficiently different from D.

6 Concluding remarks

The new knowledge that has grown out of the two projects described in this paper has underlined the importance of a full understanding of the scaling laws governing aerosol sampler performance, and identified contrasting experimental methods.

The first method involves an extension of what is referred to as the "conventional" approach, in which scaled aerosol sampler systems are tested in a small wind tunnel while exposed to relatively monodisperse aerosols. Particles are collected by test and reference samplers respectively and assessed gravimetrically. The new studies were carried out for a modified, low flowrate version of the IOM personal inhalable aerosol sampler. It was shown that such experiments can be carried out with a very high level of repeatability, and confirmed the general validity of the scaling laws alluded to.

The second method involves a novel testing system and protocol for evaluating the performances of aerosol samplers. Here, scaled aerosol sampler systems of interest are exposed to polydisperse aerosols, again in a small wind tunnel. This time the particles are counted and sized using a direct-reading instrument (the APS). A prototype automated system based on this approach was built and evaluated in preliminary experiments to determine the performance of another modified version of the IOM personal inhalable aerosol sampler. The design of the new test system accounts for the complex fluid mechanical coupling that occurs near the sampler inlet, in particular the transition between the external flow outside the sampler and the internal airflow inside the sampler. In general, we know that such a transition leads to flow complexities that are associated with particle losses inside the sampler inlet that cannot be predicted or accounted for.[20,21] The problem was overcome by the insertion of porous plastic foam plugs into the entries of both the test and the reference samplers. Modelling of the penetration characteristics of such media is well known to be reliable from other work.[24,25] Preliminary experiments with this new system provided added confirmation of the validity of the aerosol sampler scaling laws. They also demonstrated the high potential that the approach described can be applied in a standardised aerosol testing method and protocol. However, in ongoing work towards the development of a test method that may be offered for consideration as a standardised test protocol, we are addressing the many outstanding technical questions that remain: specifically to (a) reduce the variability of the test aerosol delivery system; (b) extend the range of scaled St, R and r to make the experiments relevant to actual full-scale sampling situations; and (c) adapt the basic method to make it applicable to a wide range of aerosol sampler configurations, including ones with inlet geometries that are more complicated than the IOM and modified-IOM instruments that were the subjects of the present work. The results of such enquiries will be reported in due course.

In conclusion, we have developed two contrasting experimental approaches to the evaluation of aerosol samplers for the inhalable fraction under scaled conditions in a small wind tunnel. Preliminary results indicated that both of them are very promising for providing useful information about the performances of personal aerosol samplers like those intended for use for assessing the aerosol exposures of people in industrial workplaces. New experiments are under way towards further general validation, to reduce variability and make additional improvements, and to expand the range of sampling devices that can be tested. These will be reported separately.

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References

1 *Particle Size-Selective Sampling for Particulate Air Contaminants*, ed. J. H. Vincent, ACGIH, Cincinnati, OH, 1999.
2 T. L. Ogden and J. L. Birkett, in *Inhaled Particles IV*, ed. W. H. Walton, Pergamon Press, Oxford, 1977, pp. 93–105.
3 L. Armbruster and H. Breuer, in *Inhaled Particles V*, ed. W. H. Walton, Oxford, Pergamon Press, 1982, pp. 21–32.
4 J. H. Vincent and D. Mark, in *Inhaled Particles V*, ed. W. H. Walton, Oxford, Pergamon Press, 1982, pp. 3–19.
5 D. Mark and J. H. Vincent, *Ann. Occup. Hyg.*, 1986, **30**, 89–102.
6 L. C. Kenny, R. A. Aitken and C. Chalmers, *Ann. Occup. Hyg.*, 1997, **41**, 135–153.
7 J. H. Vincent, G. Ramachandran and A. Sreenath, *Studies of aerosol sampler performance characteristics, Final Report on research carried out under NIOSH-CDC Research Grant No. 5 RO1 OH02984-03*, 1998.
8 G. Ramachandran, A. Sreenath and J. H. Vincent, *J. Aerosol Sci.*, 1998, **29**, 875–891.
9 L. C. Kenny, G. Beaumont, A. Gudmundsson and W. Koch, *J. Aerosol Sci.*, 2000, **31(Suppl.)**, S406–S407.
10 J. H. Vincent, P. C. Emmett and D. Mark, *Aerosol Sci. Technol.*, 1985, **4**, 17–29.
11 A. M. Johnston, A. D. Jones and J. H. Vincent, *Am. Ind. Hyg. Assoc. J.*, 1977, **48**, 613–621.
12 W. D. Baines and E. G. Peterson, *Trans. ASME*, 1951, **73**, 467–480.
13 S. Sato, J. H. Vincen and D. Y. H. Pui, *J. Aerosol Sci.*, 1996, **27**, 559–573.

14 M. S. P. Gomes, J. H. Vincent and D. Y. H. Pui, *Aerosol Sci. Technol.*, 1997, **26**, 269–284.
15 *Workplace atmospheres—Assessment of performance of instruments for measurements of airborne particle concentration, Draft European Standard No. prEN13205*, Comité Européen Normalisation (CEN), Brussels, Belgium, 1998.
16 D. L. Bartley, Inhalable aerosol samplers, *Appl. Occup. Environ. Hyg.*, 1998, **13**, 274–278.
17 L. C. Kenny, *Pilot study of CEN protocols for the performance testing of workplace aerosol sampling instruments, Health and Safety Executive Report IR/L/DS/95/18*, Health and Safety Laboratory, Sheffield, UK, 1995.
18 D. Mark, J. H. Vincent, H. Gibson and W. A. Witherspoon, *J. Aerosol Sci.*, 1985, **16**, 125–131.
19 S. Paik and J. H. Vincent, *J. Aerosol Sci.*, 2002, **33**, 705–720.
20 G. Ramachandran, A. Sreenath and J. H. Vincent, *Aerosol Sci. Technol.*, 2001, **35**, 767–778.
21 A. Sreenath, G. Ramachandran and J. H. Vincent, *J. Aerosol Sci.*, 2002, **33**, 871–881.
22 K. Okazaki and K. Willeke, *Aerosol. Sci. Technol.*, 1987, **7**, 275–283.
23 S. Hangal and K. Willeke, *Atmos. Environ.*, 1990, **24**, 2379–2386.
24 J. H. Vincent, R. J. Aitken and D. Mark, *J. Aerosol Sci.*, 1993, **24**, 929–944.
25 L. C. Kenny, R. J. Aitken, G. Beaumont and P. Görner, *J. Aerosol Sci.*, 2001, **32**, 271–285.
26 A. Sreenath, J. H. Vincent and G. Ramachandran, *Appl. Occup. Environ. Hyg.*, 1999, **14**, 624–631.
27 S. Paik and J. H. Vincent, *J. Aerosol Sci.*, 2002, in press.