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New Experimental Studies of the Basic Performance Characteristics of Aerosol Samplers

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The study of the basic physical performance characteristics of aerosol samplers, like those used in the occupational hygiene setting, will provide insights to enable the improved development of new instruments and cost-effective testing procedures. These will be required as the new particle size-selective sampling criteria become the basis of new occupational exposure standards. A new body of work is being conducted, in which the factors influencing sampler performance are being investigated using idealized samplers of spherical shape in small wind tunnels. By the experimental methods described, a large amount of performance data can be acquired in a very short time. The results for wide ranges of particle size, wind speed, sampling flow rate, and sampler orientation conditions show that there are strong trends as functions of these variables. Those trends are very complicated. But it is encouraging that they are broadly consistent with recent semi-empirical models, suggesting that extensions of that type of modelling approach—supported by the large amount of new experimental data now being generated by such experiments—might provide new models of aerosol sampler performance accessible to researchers and occupational hygienists.

Keywords Aerosol Sampling, Samplers, Aspiration Efficiency

Aerosol sampling is carried out for a wide range of purposes, ranging from sampling in relation to environmental and climatological effects from aircraft high in the earth's atmosphere, to sampling in relation to human exposures and associated health effects in terrestrial living and working environments. Our level of understanding in aerosol mechanics over the past few decades has taught us that, in the act of withdrawing a sample of an aerosol from a particle-laden atmosphere, the particle size distribution of the sampled aerosol may change significantly. In turn, the mass concentration reflected by a sample taken in a given situation will be influenced greatly. In the real world of environmental and occupational hygiene, therefore, it is not surprising that different personal samplers for so-called "total" dust may provide significantly different measures of exposure (e.g., Spear et al.(1)), nor that the performances of samplers for collecting respirable dust may be quite sensitive to wind speed in certain situations (e.g., Cecala et al.(2)).

For aerosol sampling in a given situation, therefore, the questions are: how has the aerosol changed during the act of sampling, and how representative is the collected sample of the aerosol of interest? Such questions are of considerable current interest as we strive to make occupational aerosol exposure assessment—and, correspondingly, occupational exposure standards for substances occurring as aerosols—relevant to the health effects which might arise.

This article describes some of the progress being achieved as part of a wider body of work to better understand the physical factors which influence the performances of aerosol samplers. To achieve the desired objectives, experimental studies were carried out in a small wind tunnel using idealized blunt samplers of spherical shape. In this arrangement, the effects of wind speed, sampling flow rate, and sampler orientation with respect to the wind can be studied easily. The results may be interpreted in the light of what is known about the physics of the basic sampling process and to identify what still remains to be investigated. Such new knowledge will provide the foundation to enable the development of improved sampling instruments, as well as guide the development of appropriate and cost-effective sampler testing protocols.

BACKGROUND

Practical aerosol samplers come in a wide variety of shapes and sizes, ranging from the more idealized sharp-edged probes of the type used for sampling in stacks and ducts and from aircraft, to the more complex, blunt configurations used in occupational and environmental hygiene. We know that the air movement near any of these samplers is distorted by the presence and aspirating action of the sampler. This, in turn, influences the motion of suspended particles both outside the sampler and inside it as particles are being transported to the sensing zone or filter (e.g., by the effects of inertial, gravitational, and electrostatic forces).

Aerosol sampling science has striven to understand the nature of such effects so that samplers can be designed to either (a) minimize or reduce them, or (b) control them in a way that makes sampling performance match a given particle size-selective criterion. A considerable body of work has emerged over the years, including both mathematical and experimental studies, much of which has been extensively reviewed elsewhere.[3,4]

Recent research has set out to investigate aerosol sampling science specifically from the standpoint of connecting what has been learned from such previous studies with how aerosol sampling is carried out in the real world. The gap that exists concerns the roles of the shape and state of symmetry of the sampling device and its orientation with respect to the prevailing external air motion. The challenge is considerable, not least because the air flow in the vicinity of an aerodynamically blunt body with aspiration placed at large angles with respect to the wind is itself very complicated and—to this day—not at all well-understood. Our own recent research[5] has shed considerable light on this matter. It shows, in particular, that the sampled air flow must always enclose the sampling orifice regardless of its orientation, with the result that, at very large orientations with respect to the wind, the boundary layer is stabilized and flow separation at the sampler surface is suppressed. This, in turn, means that the description of the flow upon which, ultimately, a physical model for sampler performance can be based, is likely to be simpler than previously expected.

Much current interest is driven by the special case of a small personal sampling device which is worn on the torso (i.e., in the lapel region) of a worker and carried with him or her throughout the working day. Such devices are widely used in occupational hygiene for the purpose of assessing the health-related exposure of the worker, and are required to collect particles in a manner that reflects how such particles are inhaled. Only in that way can the measured exposure be expected to correlate with the risk arising from the exposures. Standards-setting bodies and occupational and environmental regulatory jurisdictions around the world are now requiring that aerosol sampling should be carried out according to this philosophy. Yet, as has been reported in many laboratory and field studies, most of the personal samplers which are used by occupational hygiene practitioners do not meet such criteria.[6,7] Unfortunately, aerosol sampling science has not yet reached the point where new, better personal samplers can be designed from the outset with the desired performance. As a result, progress has been achieved primarily by the empirical testing of candidate samplers in wind tunnels, accepting only those which happen to meet the criteria in question and rejecting the others.

For the specific case of personal sampling, the experimental problems involved in such testing are formidable. It is widely held that the samplers to be tested should be mounted on a full-size torso, because we know that testing them in isolation does not give relevant results. In turn, this suggests that the experiments must be carried out in a sufficiently large wind tunnel to accommodate the sampler/torso system with minimum wind tunnel blockage problems. This therefore requires a wind tunnel of cross-section at least 1 m^2, bringing with it the technical difficulty of achieving uniform air flow and aerosol concentration distributions. As a result, such experiments, as exemplified most recently by those carried out as part of a large European study,[8] have been very difficult and, although they have achieved excellent results, they were extremely time-consuming and the results were obtained at great cost. So the idea is now dawning that this approach might not be realistic as the basis for a long-term standardization and testing strategy.

Recent research, however, is starting to point the way towards a workable alternative approach. In one study carried out in Professor Klaus Willeke's laboratory,[9] it was shown that the performances of some personal samplers mounted on relatively small bluff bodies in a much smaller wind tunnel than the ones used in the other studies referred to above gave results which were in close agreement with those large-scale studies. In a study carried out in our own laboratory,[10] it was shown that scaling laws can be developed which suggest a scaling down not only of the physical dimensions but also the range of particle sizes that need to be used in the experiments. Such scaling allows the use not only of a small wind tunnel (where highly constant test aerosol can be injected to provide very uniform spatial aerosol distribution) but also the application of direct-reading detection techniques by which very copious amounts of aerosol sampler performance data can be acquired very rapidly. Such research opens the door to testing procedures for aerosol samplers which are likely—if they can be validated—to be much more universally acceptable, not only to aerosol scientists but to occupational hygienists.

PHYSICAL BASIS

The overall performance of an aerosol sampler is governed by particle behavior outside the entrance to the sampler as it is drawn toward the sampling orifice, and inside the sampler before it reaches either the collecting or sensing zone. The most fundamental index of performance relates to the first part, because this is the most strongly influenced by external factors such as wind speed and direction. It is best expressed in terms of *aspiration efficiency* (A), where

$$A = c_s / c_o \qquad [1]$$

where c_s is the concentration of aerosol entering through the plane of the sampling orifice and c_o is the aerosol concentration in the undisturbed free stream upwind of the sampler. Here the underlying aerosol physics dictates that A is a strong function of particle size, sampling flow rate, wind speed, sampler orientation, and sampler size and shape. For a personal sampler worn on the lapel of a worker, the body of the wearer becomes—in the aerodynamic sense—an integral part of the sampler system. In this way, we see that A is likely to be quite different for a personal sampler mounted on the body than for the same sampler operated as a separate, isolated area sampler. Further, in equation (1) there is the underlying assumption that the air velocity and aerosol concentration upwind of the sampler are spatially uniform. For experimental aerosol sampler research in large wind tunnels like that which has characterized recent studies of personal samplers mounted on mannequins, this has presented very considerable technical challenges to the experimenters. With this in mind, and cognizant of the scaling laws which are now available to us which will enable us to relate the results to full-scale,[8] the current research was carried out in a small wind tunnel.

Aspiration efficiency may be expressed as a function of the variables governing particle transport in the vicinity of the sampler. For moving air, where inertial forces are expected to predominate, it may be written in the general dimensionless form

$$A = f(St, U/U_s, \delta/D, \alpha, B) = f(St, \phi, R, r, \alpha, B) \qquad [2]$$

where $St = d_{ae}^2 \gamma^* U/18\eta\delta$, $\phi = \delta^2 U_s/D^2 U$, $R = U/U_s$ and $r = \delta/D$. In these relations, St is the Stokes' inertial parameter which embodies the main physics of the sampling process, reflecting the ability (or otherwise) of a particle to follow a diverging or converging airflow, d_{ae} the particle aerodynamic diameter, U the freestream air velocity, U_s the mean air velocity at the sampling inlet, δ the width of the sampling orifice, D the characteristic dimension of the sampler, α the sampling inlet orientation with respect to the wind, and B an aerodynamic shape factor (or "bluntness"). In addition, γ^* is the density of water (10^3 kg/m^3) and η the viscosity of air. Physically, the quantity ϕ is the ratio of the sampled air volume to that which is geometrically incident on the sampling system. It is noted that, in equation (2), neither the conditions of Reynolds' number or turbulence in the moving airstream are specified because the dependencies on these are relatively weak.

Equation (2) provides an initial basis for examining the data obtained in the experiments described below.

METHODS

Wind Tunnel

The experiments described in this paper were conducted in the small wind tunnel shown in Figure 1. The experimental arrangement is described more fully elsewhere.[10] It features a test section measuring 0.3 m × 0.3 m in cross-section and 1.8 m in length, with a contraction at its entry to reduce the propagation of large-scale turbulence to the test section. Air is drawn through a bank of HEPA filters into the wind tunnel by a centrifugal fan, exiting back into the laboratory through a diffuser and another bank of HEPA filters. In the experiments described here, well-defined free stream turbulence in the test section was generated by the upstream placement of a lattice-type screen.

Test Aerosol Generation

Polydisperse glass microbead powders (Cataphote Inc., Jackson, Mississippi) were aerosolized by means of a powder disperser (BGI Inc., Waltham, Massachusetts, Model NBS-II) with a venturi-type aspirator, providing test aerosol in the range of particle aerodynamic diameters (d_{ae}) between about 1 and 30 μm. The aerosol was then passed through a 2 mCi Kr[85] charge neutralizer (Model 3012; TSI Inc., St. Paul, Minnesota), and then through a 90° bend before injection into the wind tunnel air

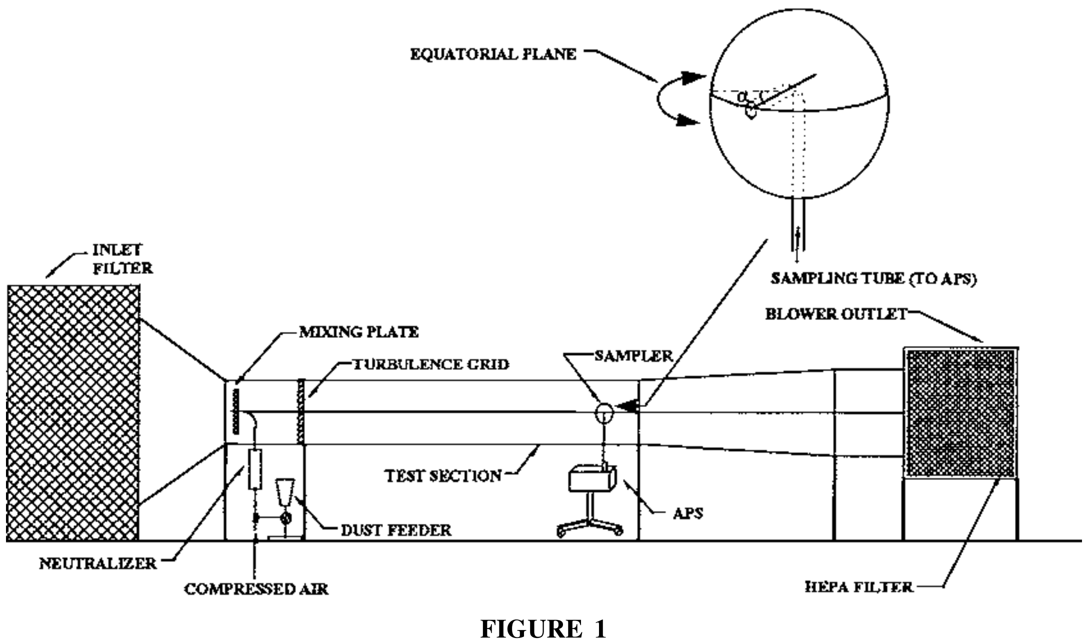

FIGURE 1
Schematic of the experimental set-up used in this research.

flow. The particles were delivered with sufficient air velocity to ensure that particle agglomerates were broken up. Prior to the experiments, the glass beads were stored in a heated oven and then sieved to remove any large agglomerates. At the time of the experiments, an infrared lamp was used to maintain the heat in the dust in the disperser to reduce moisture adsorption. We were thus able to achieve a highly constant, agglomerate-free aerosol output constant to within ±1% for periods of up to three hours.

The Test Sampler and Detection System

For the experiments reported in this article, we employed two idealized blunt aerosol samplers comprising acrylic spheres of diameter (D) equal to 3.175 and 6.350 cm, respectively, each with a single entry orifice of diameter (δ) 0.635 cm. A thin stainless steel tube was embedded inside each sphere with its entrance flush with the spherical surface. The sampled aerosol entered the sampler through this tube that was connected directly to an *aerodynamic particle sizer* (APS Model 3310, TSI Inc., St. Paul, Minnesota). By this means, the sampled particles were measured and counted into size bins between 0.5 and 30 μm, and the data were stored in a personal computer that also controlled the APS operation. The overall sampling system was arranged in such a way that the orientation of the entry orifice with respect to the freestream (α) could be varied from 0° to 180° in the horizontal (equatorial) plane while keeping fixed the orientation of the whole length of the tube with respect to the direction of the gravitational force (see inset in Figure 1). This ensured that particle losses along the main length of the tube associated with particle deposition due to gravitational and other forces remained unchanged as α was varied.

Although the sampling flowrate for the APS itself was fixed at 5 Lpm, the actual sampling flowrate (Q) could be varied above and below that figure by the deployment of an auxiliary air flow and a tapered flow divider at the entrance to the APS arranged. This was arranged such that aerosol sampling into the APS itself was always isokinetic. In the experiments, the aerosol generation rate was adjusted so that the APS always provided particle counts for each particle size bin in the range from 10 to 20 particles/cm^3, thus providing good count statistics with minimal coincidence problems. All APS particle count raw data were corrected, as required, for "phantom" particle counts[11] arising from the dual particle detection system employed in this particular model of the instrument (reported to be absent in more recent APS versions). In the particular correction method adopted, data from experiments with thin-walled probes were compared with calculated aspiration efficiency from well-established theory, and the comparison was used to determine the coefficients for making the desired particle count adjustments across the particle size range of interest (to be published separately).

During all the experiments reported here, the whole surface of each test sampler was sprayed with silicone grease to prevent particle bounce and hence secondary aspiration. Further, to reduce unwanted electrostatic effects, all wind tunnel and sampler surfaces were sprayed with anti-static fluid at the beginning of each experiment, and the test sampler, the wind tunnel, and all instruments were grounded.

Measurements of Sampling Efficiency

In what follows, the results are described in terms of what we refer to here as *sampling efficiency* (say, E) (as opposed to the aspiration efficiency referred to already). This is because the strict definition of aspiration efficiency specifies that it should relate only to particles passing through the plane of the entry. But it is known from the work of Willeke's group over the years (e.g., some as recently reported by Grinshpun et al.[12]) that particle losses may occur inside the entry tube very close to the plane of the entry. Such losses are related to the physical coupling between the external air flow outside the sampler and the internal air flow just inside the sampler entry. They arise from a combination of boundary layer effects (which decelerate the particles so that gravity can bring about deposition), *vena contracta* effects (by which particles are brought into contact with the sampler internal walls by their motion in the recirculating separated air flow just inside the sampling orifice), and impaction effects (by which particles impact directly onto upwind-facing internal walls of the sampler entry by virtue of their inertia in the approaching external air flow). Because such effects are expected to depend on the orientation (α) of the sampler, as well as other variables, then it is not possible to separate out this contribution to sampler performance in the experiments described. The implications of this are discussed later.

With this in mind, sampling efficiency for the samplers described was investigated experimentally for various sets of experimental conditions, and a primary goal was to examine how it

TABLE I
Matrix of test conditions studied in the experiments described in this article

Primary variable	Secondary parameters	Conditions studied
Sampler diameter (D)		3.175 and 6.35 cm
Sampling orifice diameter (δ)		0.635 cm
Wind speed (U)		2, 4 and 6 m/s
Sampler orientation (α)		0° to 180°
Sampling flow rate (Q)		2, 5, and 20 Lpm
Particle aerodynamic diameter (d_{ae})		0 to 30 μm
	$r = \delta/D$	0.1 and 0.2
	$R = U/U_s$	0.38 to 3.8
	$St = d_{ae}^2\gamma^* U/18\eta\delta$	Less than 0.001 to greater than 1

Note: γ^* is the density of pure water and η is the viscosity of air.

varied as a function of α. In the experiments, for each individual measurement the APS-measured particle number concentration for a given value of α was compared with that obtained for the forwards-facing case ($\alpha = 0°$), so the quantity we obtained was E_α/E_0. Actual aspiration efficiency at angle α (E_α) may, if desired, be determined easily by reference to that for the forwards-facing case ($E_{\alpha=0}$), which, in turn, may be calculated reliably using blunt sampler theory.[3,4] That is,

$$E_\alpha = \frac{c_\alpha}{c_0} = \frac{c_\alpha}{c_{\alpha=0}}\frac{c_{\alpha=0}}{c_0} = \frac{c_\alpha}{c_{\alpha=0}}E_{\alpha=0}, \qquad [3]$$

where c_α is the number concentration measured at orientation α and c_0 is the freestream concentration. In practice, for each measurement of E_α, the number concentration was measured eleven times: six times at the forwards-facing orientation to provide values of $c_{\alpha=0}$, and five times at orientation α to provide c_α, in the sequence '0-α-0-α-0-α-0-α-0-α-0'. This was permitted by the constancy of the test aerosol delivery rate. The ratios were averaged to obtain $E_\alpha/E_{\alpha=0}$ for each experimental condition, from which E_α could easily be extracted as indicated above (under the reasonable assumption that, for forwards-facing, $E_{\alpha=0} \approx A_{\alpha=0}$).

RESULTS

Experiments were carried out for a wide range of test conditions, as shown in Table I. Using the experimental method described, a very large amount of data can be acquired very quickly. It is possible here only to show a small representative selection to highlight the main trends that might in turn be related to what is known from aerosol sampling theory. By way of illustration, Figure 2 shows some typical data plotted in the form

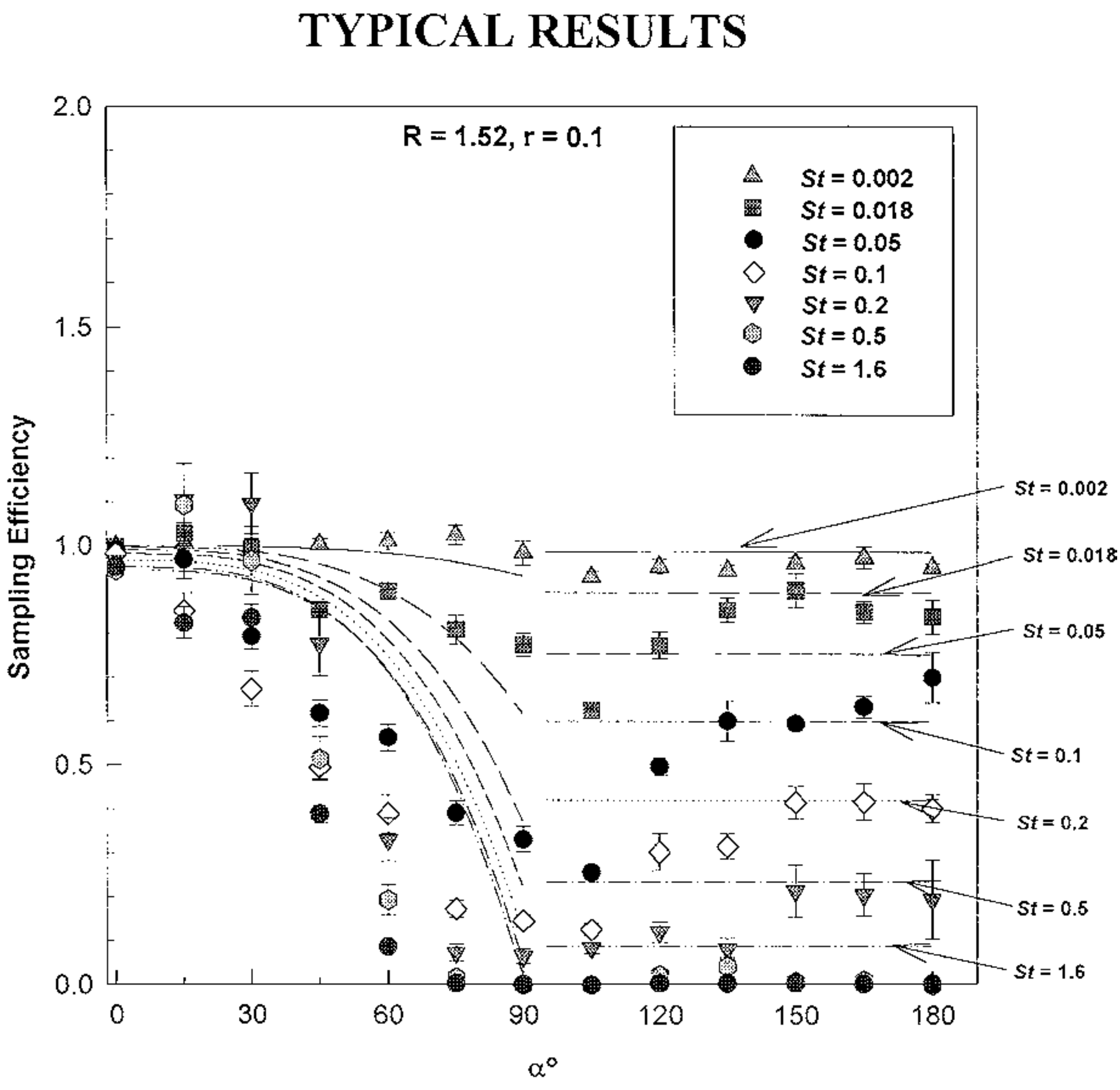

FIGURE 2
Typical experimental results for sampling efficiency (E) as a function of sampler orientation (α) for a range of Stokes' number (St). Also shown are calculated curves based on the models of Tsai et al.[12]

of E versus α for a range of Stokes' number (St). This brings out the important trend associated with orientation of the blunt sampler, something that has been largely missing from most previous experimental such research. It is seen for small St that E remains close to 100 percent over the full range of α up to 180°, not surprisingly because inertial forces are very weak. But for larger St, E first falls as α increases towards 90°, but then rises again. The amount of the "dip" increases as St increases, while that of the corresponding subsequent rise decreases. Eventually, for large St approaching unity (where inertial forces are strong), E falls rapidly to zero for α somewhat less than 90° and does not rise again. In general, for St greater than about 0.1, the change in E for α beyond 90° is small. These data are for just one combination of r and R; but the same general trends are seen for the other conditions studied (and not shown here).

Again for the purpose of illustration, Figure 3 shows data for another set of conditions of r and R, plotting E this time as a function of St for various values of α up to 180°. These graphs show the strong dependency of E on St, and hence on inertial forces, as St increases above about 0.01. They, like Figure 2, also show that sampling efficiency falls to zero for large St and α beyond about 90°. Further, changes in the shape of E versus St are small in this range.

DISCUSSION

Firstly we need to further address the aforementioned distinction between aspiration efficiency (A) and sampling efficiency (E). In almost all the previous theoretical and experimental studies of sampler performance, ranging from the extensive investigations of cylindrical thin-walled probes to more complicated blunt sampler configurations, A has been the object to be calculated or measured. So far, in our research, we have not be able to explicitly extract A. However, it may be argued that what we have obtained by measuring E is a more relevant metric of aerosol sampler performance. That is, the particle losses that occur during the coupling of the sampler's external and internal flows represent an important and integral part of its basic performance that is inevitable in practical reality. Nonetheless, it is important to determine the relative magnitude of this effect in relation to aspiration efficiency itself, and this will be the subject of future investigations to be reported separately.

Tsai and Vincent[13] examined the available experimental data for both thin-walled and blunt samplers at large angles with respect to the wind, 90° and 180°, respectively, and used them to arrive at expressions for A_{90} and A_{180}. For A_{90}, an adjustment of the explicit expression suggested earlier for the thin-walled probe by Vincent et al.[14] was made by introducing a single term involving r to account for the difference in the diameters of the sampler body and the sampling orifice. For A_{180}, the model was further extended to account for impaction of particles onto the leading edge of the sampler. Thus, by fitting the unknown coefficients to the available data, Tsai and Vincent obtained

$$A_{90} = 1\Big/\left[1 + 4(2.21\ \mathrm{St})(R/r)^{1/2}\right]$$

and

$$A_{180} = 1\Big/\left[1 + 4(4.5\ \mathrm{St})(r^2/R)^{1/3}r^{-0.29}\right] \qquad [4]$$

In a later paper, Tsai et al.[15] interpolated between these expressions, along with what is known for A_0 (i.e., $\alpha = 0°$), in order to describe A_α for the range of α from 0° to 180°. The coefficients in this expression were fitted with respect to available orientation-averaged data from wind tunnel experiments with a range of rotating-head aerosol samplers of the type which had been proposed as static samplers for collecting the inhalable fraction. Thus, Tsai et al. developed the expressions

$$A_\alpha = A_0 - (A_0 - A_{90}) \cdot (\alpha/90)^\mu \quad \text{for } 0° \le \theta \le 90°$$

and

$$A_\alpha = A_{180} \quad \text{for } 90° < \alpha \le 180° \qquad [5]$$

in which $\mu = 90.49 \cdot R^{-2.31}\, r^{1.01}$. Closer inspection of the Tsai et al. model reveals that it contains a discontinuity at $\alpha = 90°$. But this is an artifact of the particular mathematical formulation shown and has no physical meaning. Furthermore, it has no significant quantitative effect because aspiration efficiency does not change as α increases beyond 90°, so that A_{90} and A_{180} are close to one another.

Curves for aspiration efficiency calculated from the two sets of equations (3) and (4) are included as the solid lines on the graphs shown in Figures 2 and 3. In Figure 2 the discontinuity referred to above is clearly seen. In both figures it is seen that, notwithstanding the acknowledged difference in the calculated A and the measured E, agreement between these and our new experimental data are fair. Certainly, the model follows the main trends exhibited by the experimental data. By contrast, the calculated values of A based on the earlier blunt sampler model of Vincent,[16] also plotted in Figure 3 (see dashed lines), are in poor agreement with the experimental results.

From the picture which emerges from the above, it is clear that further model development is needed, not only for aspiration efficiency but also for the losses that occur close to the sampler entry. In this regard, it is worth reiterating the generally accepted view that the development of physical models for describing aerosol sampler performance is still at a fairly rudimentary stage. The fact is, the scenario is extremely complicated, as can be deduced even from the functional statement given in equation (1). Full mathematical treatments require knowledge about the air flow about samplers which, although considerable progress in that direction was reported in our earlier article,[5] is not yet available. It would appear that computer fluid dynamical (CFD) simulations have not so far been very successful in

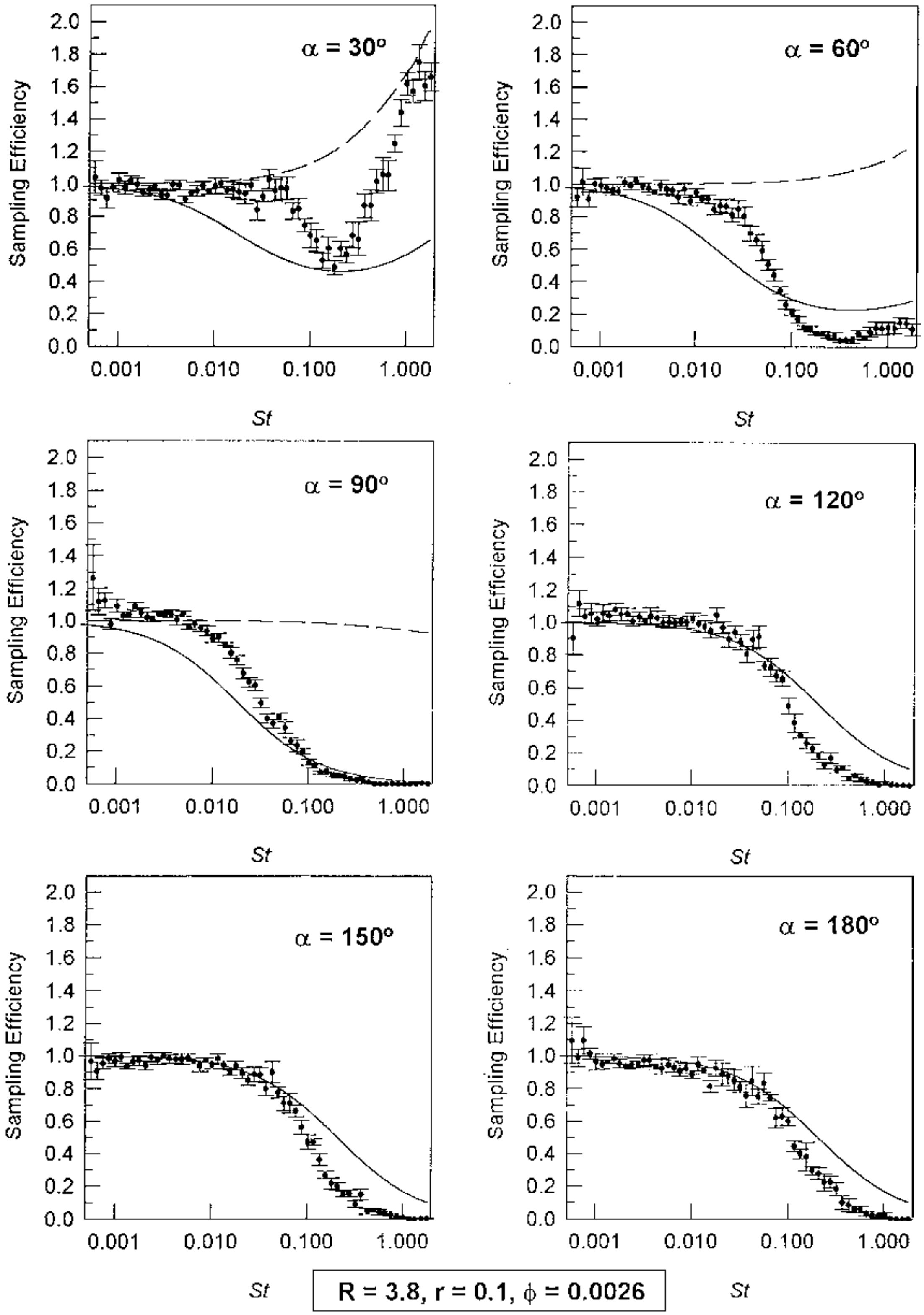

FIGURE 3
Typical experimental results for sampling efficiency (E) as a function of Stokes' number (St) for the full range of sampler orientation (α) from 0° to 180°. Also shown are the calculated curves for aspiration efficiency (A) based on the models of Tsai et al.[12] (solid lines) and Vincent[13] (dashed lines for α up to 90° only).

dealing with complex bluff body flows where there is aspiration, especially for large orientations with respect to the wind. This is particularly true for the sorts of CFD routines that can be run on the desk top personal computers available to most researchers. With this in mind, it is most likely that progress toward the sorts of aerosol sampler performance models that are accessible to most developers and users of aerosol sampling instruments model will be via extensions of the semi-empirical physical models like those referred to here. Our own work is moving in that direction, making use of the very large data set that is being acquired using the experimental system and methods described in this article.

CONCLUSION

Aerosol samplers continue to be important tools for occupational hygienists. The importance of a proper understanding of the performances of specific devices, and how these might relate to specific exposure assessment criteria, is given sharp prominence by the progress which is being achieved toward the development and implementation of new particle size-selective criteria for health-related aerosol sampling.[17,18] In the future, to meet such sampling criteria as the basis of occupational exposure standards, aerosol samplers must demonstrably match certain performance requirements over the wide ranges of conditions for which they are used in workplaces and elsewhere. This means, therefore, that instruments must be designed from the outset to meet those criteria. In turn, scientifically based, reliable and cost-effective sampler testing procedures will be needed. The development of improved sampler performance models will lead in turn to a sounder basis for the scaling laws which will allow progress toward the implementation of testing procedures under small-scale conditions (as suggested by Ramachandran et al.[10]). Basic—but pragmatic—research like that described in this article is the only way toward providing the necessary framework for the sound achievement of these practical goals.

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