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Aerosol Science 33 (2002) 871–881

Journal of
Aerosol Science

www.elsevier.com/locate/jaerosci

Aspiration characteristics of idealized blunt aerosol samplers at large angles to the wind

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Received 11 May 2001; received in revised form 26 December 2001; accepted 27 December 2001

Abstract

The research described in this paper extends the body of work contained in earlier publications in which aerosol sampling aspiration efficiency was studied in a small wind tunnel for simple, idealized sampler geometries. These studies are aimed at providing generic knowledge about the physical and functional behaviors of such systems that can then be generalized to sampling systems of more practical interest. In this paper, attention is focused on the little-researched case of a blunt sampler facing away from the prevailing wind velocity. The results show, that for angles greater than 90° with respect to the wind, aspiration efficiency and particles losses inside the sampler close to the entry are constant as a function of α. This in itself may have some practical usefulness since it enables the definition of a regime of aerosol performance that is relatively "well-behaved".

These results are in marked contrast to what has been learned from the same body of work for sampler behavior when facing forward with respect to the wind. Here not only does aspiration efficiency vary sharply with orientation, but so too does the particle entry loss. From this it is concluded that no general model of aspiration efficiency can be available so long as experimental results embody unknown entry loss biases. With this in mind, caution is recommended in field sampling or in laboratory experiments where the measurement does not explicitly include such entry losses. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Aerosol sampling; Blunt bodies; Aspiration efficiency

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0021-8502/02/$ - see front matter
PII: S0021-8502(02)00041-1

1. Introduction

Aerosol sampling systems like those used in environmental and occupational hygiene have been defined as aerodynamically "blunt", acknowledging that the sampler body in all such cases provides significant blockage to the flow. This applies also to the cylindrical thin-walled probes that have been the most widely studied and have many practical applications, for example, the representative sampling of particulates in stack gases. Even thin-walled probes must have finite tube thickness and so exhibit finite bluntness. However, thin-walled probes may usefully be described as a limiting case of a much wider family of so-called "blunt" aerosol samplers. Knowledge gained from studies aimed at understanding the performance characteristics of thin-walled aerosol sampling probes has been useful in understanding the much more complex sampling systems of wider interest to environmental and occupational hygienists. So, out of the theory for aspiration efficiency for thin-walled probes has grown a limited body of knowledge of the factors controlling the aspiration efficiencies of blunt samplers. It was realized as long ago as the early 1980s that studies of idealized versions of such blunt samplers, involving extensions of what had been learned from the experience with thin-walled probes, had an important role in providing a link with the much more complicated sampler configurations that pertain to many practical situations.

Initially, progress in understanding the physics of blunt aerosol sampling was slow due to the sparseness of experimental data by which to validate and test the various mathematical and physical models that were proposed. With this in mind, a new body of work was initiated in the 1990s to develop new experimental methods for studying aerosol sampler performance. The aim was to produce large amounts of data upon which to base a foundation of new theoretical knowledge that would in turn help in the design of new practical aerosol samplers for specific applications and also aid in the interpretation of results obtained using existing ones. The research, carried out in our laboratory for blunt samplers of simple spherical shape, provided data that: (a) elucidated the nature of air flows, especially at very large angles of the inlet with respect to the wind (Sreenath, Ramachandran, & Vincent, 1997); (b) identified new options for the rapid testing of aerosol samplers in small-scale wind tunnels (Ramachandran, Sreenath, & Vincent, 1998); (c) provided new data on which to base initial evaluation of existing theoretical aspiration efficiency models (Sreenath, Ramachandran, & Vincent, 1999a); and (d) pointed the way towards the application of aerosol sampler scaling laws in the development of new sampling instruments (Vincent, Ramachandran, Thomassen, & Keeler, 1999).

One aspect of aerosol sampler performance that emerged during this research was the importance of the physical coupling between the air flow outside the sampler and that just inside the sampler near the inlet. Such coupling had been examined previously by Willeke and his co-workers, who identified the roles of the growth of the boundary layer on the inside wall of a tube-shaped sampler facing the wind (Okazaki & Willeke, 1987) and the *vena contracta* just inside the same sampler at other orientations (Hangal & Willeke, 1990). Now it has emerged that such effects are very complicated functions of particle size, windspeed, sampling flowrate and sampler orientation, even for the relatively-simple, thin-walled sampling probes (Sreenath, Ramachandran, & Vincent, 2001).

This paper examines the conditions under which current theoretical knowledge is sufficient to permit a description of what occurs during blunt sampling and those where it is not. The experiments were carried out for a simple, spherical-shaped idealized blunt sampler. Special attention is focused on very large angles with respect to the wind, greater than 90°, for which very little research—

experimental or theoretical—has been conducted. The results may have important implications for future aerosol sampler research and for practical applications.

The work described here builds upon a large body of research that has been carried out in our laboratory over several years, and this is reflected in our other works cited here. In addition, however, it also draws heavily on the experiences of others in the field of aerosol sampling science. These include the important earlier experimental wind tunnel studies of thin-walled samplers by Willeke and his colleagues (cited above) and of idealized blunt samplers by Chung and Ogden (1986). Several workers have conducted experimental studies of less idealized, "real-world" samplers and related the results to theoretical blunt sampler models (e.g., Li & Lundgren, 2002). Other influential research includes the mathematical and numerical studies for blunt samplers by Ingham and his colleagues (e.g., Ingham & Wen, 1993), Erdal and Esmen (1995), and others.

2. Physical basis

Aspiration is the physical process of drawing an aerosol from an environment and through the plane of the sampler orifice. For a sampler collecting aerosols uniformly distributed in a uniform freestream, aspiration efficiency (A) is defined as the ratio of the particle concentration entering through the plane of the sampler entry (c) to that in the undisturbed upstream air (c_0) (Vincent, 1989). This is the most fundamental index of performance for any sampler, and depends on the Stokes number ($St = d_{ae}^2\gamma^* U/18\eta\delta$), the ratio of the freestream velocity (U) to the sampling velocity at the tube entrance (U_s) ($R = U/U_s$), the ratio of the size of the sampling orifice to that of the sampler body ($r = \delta/D$), and the orientation of the sampler to the freestream (α). Here, St embodies the effects of particle inertia, d_{ae} is the particle aerodynamic diameter, δ the width of the sampling inlet, D the width of the sampler body, γ^* the density of water (10^3 kg/m^3) and η the viscosity of air.

Although A is the most basic index of performance for the sampling system, the actual performance in practice is complicated by the fact that the aspirated aerosol has to adjust to the new flow conditions inside the sampler. This means that there will be particle losses in the so-called "entry region" directly as a result of the coupling between the external and internal flows. In addition, beyond the entry region, the aerosol will usually pass through a further transition before it reaches the sensing or collecting zone. Thus there are three distinct regions that need to be discussed in relation to overall sampling performance. With this in mind, overall sampling efficiency (E) may be expressed as (see Fig. 1)

$$E = AP_{entry}P_{tube}, \tag{1}$$

where P_{entry} is the entry penetration efficiency given by the ratio of particle concentration downstream immediately beyond the entry region of the inlet to that in the plane of the entry ($P_{entry} = c_1/c$) and P_{tube} is the ratio of particle concentration at the collection or sensing medium to that just downstream of the entry region ($P_{tube} = c_2/c_1$). Note that the three terms on the right-hand side of Eq. (1) are the efficiencies of transmission through the regions indicated in Fig. 1.

In experiments to determine aspiration efficiency, depending on how they are carried out, it remains a significant challenge to unravel the individual contributions of the terms in Eq. (1) so that A itself may be isolated.

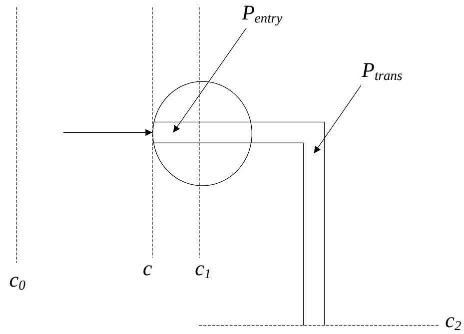

Fig. 1. Schematic of the blunt sampler system, drawn to highlight the separate regions where particle losses may occur.

3. Experimental

3.1. Apparatus

The experimental facilities and methods used in this research have been described in detail elsewhere (Ramachandran et al., 1998), so only a short summary will be given here. The experiments were conducted in a small open-loop wind tunnel, with a working section 0.3 m $\times$ 0.3 m in cross-section and 1.8 m in length. Turbulence with well-defined intensity and length scale was generated by the use of a lattice-type screen placed at the entrance to the working section, such that turbulence intensity and length scale at the working region of the wind tunnel (i.e., where the sampler was located) were estimated to be about 5% and 0.7 cm, respectively (based on the still-reliable data of Baines & Peterson, 1951).

Polydisperse glass microbead powders (Cataphote Inc., Jackson, MS), with a density of 2.45 g cm^{-3}, were used to generate the test aerosol. These were aerosolized by means of a powder disperser (BGI Inc., Waltham, MA, Model NBS-II) with a venturi-type aspirator, providing test aerosol in the range of d_{ae} between 1 and 37 μm. The aerosol was then passed through a 2 mCi Kr^{85} charge neutralizer (Model 3012; TSI Inc., St. Paul, MN), and then through a 90° bend into a 0.76 cm diameter injection nozzle. Prior to each experiment, the glass beads were stored in a heated oven to reduce the moisture content, then sieved to remove any large agglomerates. An infrared lamp was used to maintain the temperature of the powder in the disperser sufficient to reduce moisture adsorption, agglomeration and clogging of the dust hopper. In this way, a steady, agglomerate-free aerosol output (number concentrations constant to within $\pm$ 1%) was achieved.

The primary subject of the experiments described in this paper was an idealized spherical blunt aerosol sampler. Two such samplers were built, of different sizes, one with diameter $D = 6.35$ cm and the other with $D = 3.175$ cm. Each had a single entry orifice of diameter $\delta = 0.635$ cm. Each was constructed by gluing together two solid acrylic hemispheres. Recesses were carved in the hemispheres so that a stainless steel tube (I.D. = 0.635 cm) could be embedded inside the resultant sphere with its entrance flush with the spherical surface. The sampled aerosol entered the sampler through this tube. The tube was connected directly to an Aerodynamic Particle Sizer (APS, Model 3310, TSI Inc., St. Paul, MN) by which the sampled particles were measured and counted into bins representing discrete small particle size intervals in the range of aerodynamic diameter from

0.5 to 30 μm (with the data 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. This ensured that particle losses over the main length of the tube—except for the region immediately adjacent to the inlet—remained unchanged as α was varied. The sampling flowrate for the APS was fixed at 5 l/min. However, different flowrates through the sampler itself were possible by virtue of the tapered flow divider placed immediately ahead of the APS whereby air could be added or subtracted as required without disturbing the aerosol concentration (Sreenath et al., 1999a). In the experiments, the aerosol generation rate was adjusted to provide particle counts for each bin in the range from 10 to 20 particles cm^{-3}, thus minimizing coincidence problems. In any case, all particle counts were corrected for the biases associated with coincidences and "phantom" particles now known to be associated with the use of this model of the APS (Sreenath, Ramachandran, & Vincent, 1999b). In preliminary studies, experiments were carried out with the external surfaces of the blunt sampler both greased and ungreased, in order to identify the occurrence of particle bounce or blow-off. No differences were observed. Nonetheless, as a precaution against the possibility of such effects, for all the experiments described here, the whole surface of the sampler was sprayed with silicone grease prior to each run to prevent secondary aspiration that might distort the measured inlet efficiency measurement

Finally, from a combination of hot-wire anemometry and APS measurements, both air velocity and particle concentration were uniform to within ± 5% over the central part of the working section of the wind tunnel.

3.2. Experimental rationale

Using the experimental system described above, *relative aspiration efficiency* for the sampler described was determined experimentally as a function of α. In principle this requires that all measured particle number concentrations are referred to those obtained for the forwards-facing case (i.e., $\alpha = 0°$), so that relative aspiration efficiency is expressed as $A_\alpha / A_{\alpha=0}$. Thus

$$A_\alpha = \frac{c_\alpha}{c_0} = \frac{c_\alpha}{c_{\alpha=0}} \frac{c_{\alpha=0}}{c_0} = \frac{c_\alpha}{c_{\alpha=0}} A_{\alpha=0}, \tag{2}$$

where c_α is the number concentration for aspirated aerosol at orientation α and c_0 is the freestream concentration, and where A_α may be determined easily by reference to that for the forwards-facing case ($A_{\alpha=0}$), which in turn may be calculated reliably using blunt sampler theory (Vincent, 1989).

However, in reality, it is necessary to examine the extent to which the desired concentration ratio on the right-hand side of Eq. (2) really can be obtained directly using the experimental method described. We begin by defining *sampling efficiency* as

$$E_\alpha = \frac{{}_{\text{APS}}c_\alpha}{c_0}, \tag{3}$$

where ${}_{\text{APS}}c_\alpha$ is the concentration actually recorded by the APS, thus also reflecting the losses of particles by deposition inside the sampling tube between the inlet itself and the APS measuring system. But since c_0 itself cannot be determined directly, what is actually determined in our experiments is the *sampling efficiency ratio* (H_α) given by

$$H_\alpha = \frac{{}_{\mathrm{APS}}c_\alpha}{{}_{\mathrm{APS}}c_{\alpha=0}} = \frac{E_\alpha}{E_{\alpha=0}} \rightarrow \frac{c_\alpha}{c_{\alpha=0}} \frac{P_{\mathrm{entry}(\alpha)}}{P_{\mathrm{entry}(\alpha=0)}} \tag{4}$$

if it is assumed that P_{tube} in Eq. (1) is the same for all orientations of the sampler and so may be allowed to cancel out. With Eq. (2), this now leads to

$$A_\alpha P_{\mathrm{entry}(\alpha)} = H_\alpha A_{\alpha=0} P_{\mathrm{entry}(\alpha=0)}. \tag{5}$$

Since, in Eq. (5), H_α is what was actually measured in our experiments, we can only arrive at the desired A_α either if the P's cancel or can be known.

In practice, for each experiment, the particle number concentration at the APS was measured eleven times: alternating six times for the forwards-facing orientation and five times for orientation α, leading to the average value of the concentration ratio and standard error (and other statistics if desired) reflecting the experimental variability.

4. Results and discussion

4.1. Large angles greater than 90°

As stated earlier, primary interest in the work described in this paper was focused on very large angles with respect to the wind, greater than 90°. Figs. 2a–f show the product $H_\alpha A_{\alpha=0}$ as a function of St for various combinations with $R = 0.38$, 0.76, 1.52, 2.28 and 3.8 and $r = 0.1$ and 0.2, and for values of α from 105° up to 180°. The error bars on the data points reflect the standard error for each data point. For all the data sets shown, it is seen that $H_\alpha A_{\alpha=0}$ falls steadily (and, for practical purposes, monotonically) with increasing St. Variation with α is seen to be relatively weak everywhere, especially for α exceeding about 120°.

Also shown on each figure is the corresponding calculated curve for aspiration efficiency (A) from the semi-empirical model proposed by Tsai, Vincent, and Mark (1993) and Tsai, Vincent, Mark, and Maldonado (1994) for blunt samplers where the sampling orifice is located symmetrically on the body of the sampler (as was the case for the idealized samplers examined in the present work). Here, for all angles greater than (but not including) 90°, we have

$$A_\alpha = 1/[1 + 4(4.5St)(r^2/R)^{1/3} r^{-0.29}]. \tag{6}$$

This model assumes that A_α does not change at all with orientation for such large angles. This is broadly consistent with what was observed in our present experiments. However the calculated values of A_α are clearly not in quantitative agreement with the measured values of $H_\alpha A_{\alpha=0}$. Nor should they be, since—as we have discussed—they are not the same physically. But the comparison is consistent in that A_α always exceeds $H_\alpha A_{\alpha=0}$, as it should so long as particle losses during transport from the inlet to the APS are finite. Further, the difference becomes greater with increasing St, which too is consistent with the particle size-dependent losses of particles by deposition during transport through the tube from the moment they pass through the plane of the inlet.

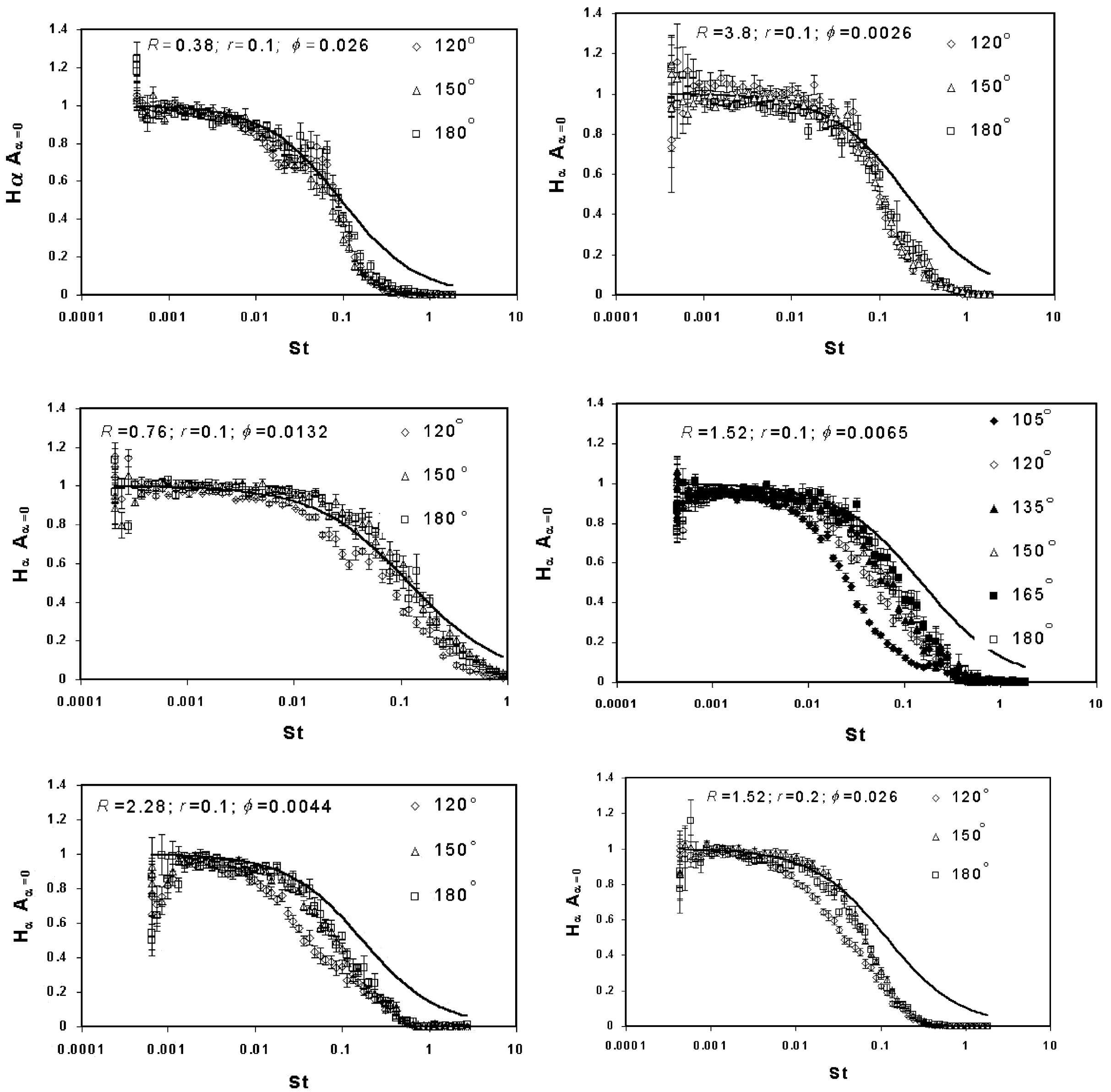

Fig. 2. $H_\alpha A_{\alpha=0}$ as a function of Stokes' number (St) for $\alpha = 120°$, $150°$ and $180°$ and a range of values of R and r: (a) $R = 0.38$, $r = 0.1$; (b) $R = 3.8$, $r = 0.1$; (c) $R = 0.76$, $r = 0.1$; (d) $R = 1.52$, $r = 0.1$; (e) $R = 2.28$, $r = 0.1$; (f) $R = 1.52$, $r = 0.2$. The solid lines are calculated from the semi-empirical model of Tsai et al. (1993, 1994).

To link up the measured $H_\alpha A_{\alpha=0}$ and the calculated A_α in Figs. 2a–f, we return to Eq. (5), and express it in the form of the *entry penetration ratio*

$$P_{\text{entry}} = \frac{P_{\text{entry}(\alpha)}}{P_{\text{entry}(\alpha=0)}} = \frac{H_\alpha A_{\alpha=0}}{A_\alpha}, \tag{7}$$

where now the object of attention is the penetration ratio that reflects how the change in orientation impacts on particle transport just inside the entry. Here all the terms of the right-hand side can be determined: $A_{\alpha=0}$ from the model of Vincent (1989), A_α from the model of Tsai et al. (1993, 1994) and H_α from our measurements. The resultant values for the penetration ratio for conditions corresponding to those contained in Figs. 2a–f are shown in Figs. 3a–f.

The entry penetration ratio is certainly of interest from the point of view of practical aerosol sampling. But the controlling fluid and particle mechanics are extremely complicated and are unlikely to be obtainable in explicit form from direct physical considerations. However, it is governed by inertial factors involving *St*, *R* and *r* in much the same way as for $A_\alpha > 90^\circ$ as expressed in Eq. (6), which itself was empirical. With this in mind, the data for the penetration ratio obtained from application of Eq. (7) were fitted to the empirical expression

$$\frac{P_{\mathrm{entry}(\alpha)}}{P_{\mathrm{entry}(\alpha=0)}} = \frac{1}{1 + k_1(St^{k_2})(\phi^{k_3})(r^{k_4})}, \qquad (8)$$

where the k-values were coefficients to be determined by regression. The fitted curve for each set of conditions is shown alongside the experimentally-determined penetration ratios in Figs. 3a–f. The agreement of the model with the data is generally quite good ($R^2_{\mathrm{adj}} = 0.894$). The model fit parameter values were $k_1 = 237.7$; $k_2 = 1.540$; $k_3 = -0.134$, and $k_4 = 1.504$. This result is helpful because we can now say with confidence that not only is sampler aspiration efficiency constant for rearwards-facing angles greater than 90°, but so too are the particle losses near the entry associated with the coupling between the external and internal flows. Although this conclusion is reached for the simple, idealized sampler geometry studied in this work, it is also likely to be true for other, more-complex sampler geometries like those found in practical aerosol sampling systems. However it has to be noted that the form of Eq. (8), and its fitted coefficients, are specific to the idealized sampler geometry studied, including not only the external but also the internal geometries.

Finally, in Figs. 3a–f, although the model follows the main trends exhibited by the data very well, it does not explain some of the finer detail. In particular, there is a notable departure in Fig. 3a for *St* in the range from about 0.05 to 0.1, where the experimental values of P_{entry} display a marked peak. No attempt to explain this detail was sought because, as had been assumed from the outset, the empirical model would likely at best describe only the main broad observed trends.

4.2. *Smaller angles up to and including* 90°

This paper has focused almost exclusively on what happens at large angles with respect to the wind. Of course, interest is drawn to all orientations, including those for forwards-facing. In many practical aerosol sampling situations, the orientation is not known and at any time can be anywhere from 0° to 180°. Typical results for angles up to and including 90° were shown in our earlier paper (Sreenath et al., 1999a), and these show trends of $H_\alpha A_{\alpha=0}$ for $\alpha < 90^\circ$ that are more complicated than for rearwards-facing and not always monotonic as a function of *St*. This is not surprising since sharply-varying aspiration efficiency as a function of small $\alpha < 90^\circ$ is well recognized.

In our studies of the simpler thin-walled probe (Sreenath et al., 2001), examination of the experimental data to obtain P_{entry} along similar lines to that described above for $\alpha < 90^\circ$ yielded a very complex empirical relationship with more fitted coefficients that were needed above for $\alpha > 90^\circ$. Although such a relationship might similarly be found for the idealized blunt sampler of the present

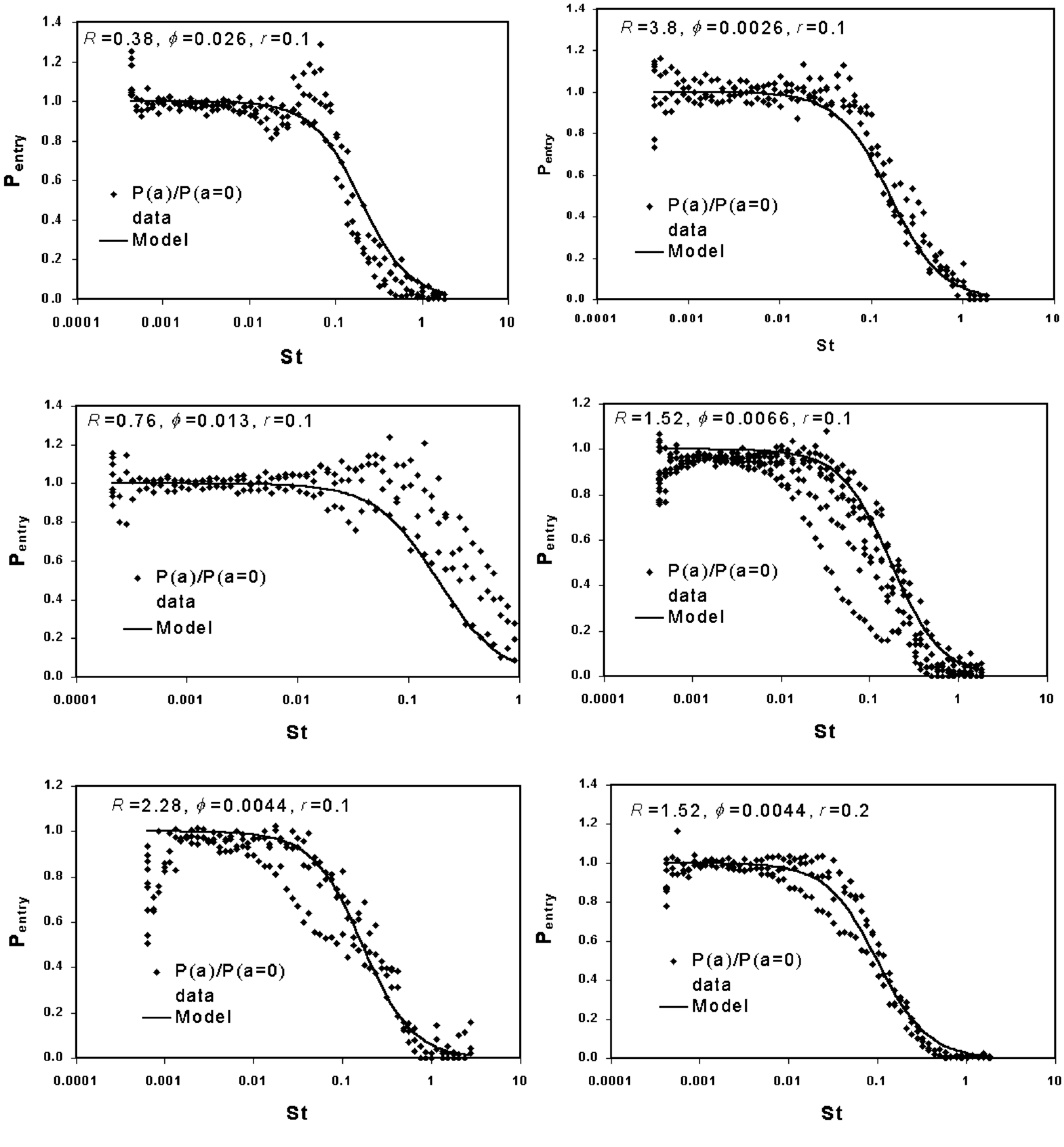

Fig. 3. Values of entry penetration ratio ($P_{\text{entry}} = P_{\text{entry}(\alpha)}/P_{\text{entry}(\alpha=0)}$), calculated from the data in Fig. 2, as a function of St and for $\alpha = 120°$, $150°$ and $180°$ and a range of values of R and r: (a) $R = 0.38$, $r = 0.1$; (b) $R = 3.8$, $r = 0.1$; (c) $R = 0.76$, $r = 0.1$; (d) $R = 1.52$, $r = 0.1$; (e) $R = 2.28$, $r = 0.1$; (f) $R = 1.52$, $r = 0.2$. The solid lines are calculated from the fitted model as expressed by Eq. (8).

experiments, it is inevitable that the relationship will be different for blunt samplers of different shape beyond the idealized sphere. So it was considered that the development of such a model for the spherical blunt sampler would have limited value, and it was decided not to pursue this.

4.3. Applications to practical aerosol sampling

The findings of this study for sampling at large angles with respect to the wind suggest some interesting practical possibilities if sampling may be constrained to take place at orientations with respect to prevailing air movements that lie beyond 90°. Here aspiration efficiency may reasonably be predicted and so too may the particle losses that take place near the sampler entry. At least they may be assumed to be independent of orientation in that range. Under such conditions, therefore, sampler performance may be considered to be quite "well-behaved". By contrast, and surprisingly (since most of the aerosol sampling research has been carried out for this regime), our knowledge about aspiration and sampling efficiencies for orientations facing the prevailing air movement remains less useful.

In general, for application of the new knowledge that has been gained from the body of work of which the studies in this paper were a part, there is increased recognition that aerosol sampler theory remains elusive in terms of its applicability to the wide range of occupational and environmental hygiene aerosol sampling situations. The largest single problem that has emerged during the more recent work lies in the bias in aerosol sampling measurement that can arise from the coupling between the air flows external and internal to the sampler, respectively (as reflected in the changing P_{entry}). This means that, in experiments or field measurements where internal entry losses are not explicitly accommodated in the design and use of the instrument, uncontrolled and unknown bias will be present. In general, the designers of aerosol samplers should recognize the difficulty associated with the unknown internal entry loss and be ready to engineer instruments in a way that by-passes the problem (e.g., by the use of cassettes that collect everything that passes through the plane of the sampling orifice).

These findings are also relevant to laboratory aerosol test procedures like those we articulated in Ramachandran et al. (1998), where the unknown internal entry loss makes it difficult to isolate the true aspiration efficiency. They are also relevant to the already widely-used procedures in which the APS, or an equivalent instrument, is used in similar protocols to make rapid determination of the particle penetration characteristics of, for example, cyclones and foam pre-selectors. For these, although entry effects are not likely to be problematical for the fine (respirable) aerosol fractions that such devices were originally intended to sample, they may be significant for the intermediate (thoracic) fraction for which there is considerable current interest. If such procedures are carried out in wind tunnels, then experimenters might think about placing the devices being tested so that they face away from the wind.

5. Conclusions

The research described in this paper extends the body of work contained in earlier publications in which aerosol sampling aspiration efficiency has been studied in a small wind tunnel for simple, idealized sampler geometries aimed at providing generic knowledge about the physical and functional behaviors of such systems that can then be generalized more widely to sampling systems of more practical interest. Here attention has been focused on the little-researched case of a blunt sampler facing away from the prevailing air motion. The results show that for angles with respect to the wind greater than 90°, aspiration efficiency and particles losses insider the sampler close to the entry are constant as a function of α. This in itself may have some practical usefulness since it enables the definition of a regime of aerosol performance that is relatively "well-behaved".

Based on what has been learned from elsewhere in this body of research, we have not yet been able to achieve a similar level of clarity in our understanding of the sampler at angles facing towards the wind. Therefore caution is recommended in field sampling or in laboratory experiments where the measurement does not explicitly include such entry losses.

Acknowledgements

This work was carried out under CDC-NIOSH Contract 5 RO1OH02984-03. The authors are grateful for this support.

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