

# The Orientation-averaged Aspiration Efficiency of IOM-like Personal Aerosol Samplers Mounted on Bluff Bodies

SAMUEL Y. PAIK and JAMES H. VINCENT\*

Department of Environmental Health Sciences, School of Public Health, University of Michigan, Ann Arbor, MI 48109-2029, USA

Received 17 March 2003; in final form 2 July 2003

This paper describes two sets of experiments that were intended to characterize the orientation-averaged aspiration efficiencies of IOM samplers mounted on rotating bluff bodies. IOM samplers were mounted on simplified, three-dimensional rectangular bluff bodies that were rotated horizontally at a constant rate. Orientation-averaged aspiration efficiencies ( $A_{360}$ ) were measured as a function of Stokes' number ( $St$ ), velocity ratio ( $R$ ) and dimension ratio ( $r$ ). Aspiration efficiency ( $A$ ) is the efficiency with which particles are transported from the ambient air into the body of a sampler, and  $A_{360}$  is  $A$  averaged over all orientations to the wind.  $St$  is a dimensionless variable that represents particle inertia,  $R$  is the ratio of the air velocity in the freestream and that at the plane of the sampler's entry orifice, and  $r$  is the ratio of the sampler's orifice diameter and the bluff body's width. The first set of experiments were instrumental in establishing a hierarchy of effects on orientation-averaged  $A$ . It was clear that compared to  $r$ ,  $St$  had a much larger influence on  $A$ . It was also clear, however, that the effects of  $St$  were overpowered by the effects of  $R$  in many cases. As concluded in previous studies,  $R$  and  $St$  were considered the most important factors in determining  $A$ , even for  $A_{360}$ . The second set of experiments investigated  $A_{360}$  of IOM samplers for a much wider range of  $r$  than examined in previous research. Two important observations were made from the experimental results. One was that the  $A_{360}$  of IOM samplers, as a function of  $St$ , did not change for an  $r$ -range of 0.066–0.4. This meant that an IOM sampler mounted on a near life-size mannequin would measure the same aerosol concentration as one not mounted on anything. The second observation was that the aspiration efficiency curve of the IOM sampler was close to the inhalability curve. This gave further evidence that the bluff body did not play a major role in influencing  $A_{360}$ , as the IOM samplers, in these experiments, were either mounted on miniature bluff bodies or on nothing at all. These observations all suggest that it is quite possible to design and test personal samplers with desired sampling characteristics using protocols that do not require full-size mannequins, which greatly simplifies the development of new samplers.

*Keywords:* aerosol sampling; aspiration efficiency; bluff body; inhalable sampling; IOM sampler; mannequin; orientation averaging; particle size-selective criteria; Stokes' number; wind tunnel

## INTRODUCTION

In the development of aerosol samplers that conform to specific, particle size-selective criteria (e.g. for environmental or occupational hygiene sampling purposes), it is important to understand the physical processes that determine how aerosols are aspirated

into sampler nozzles and inlets. In the history of the development of such understanding, the simplest scenario has involved aspiration into a sharp-edged, thin-walled probe facing the wind, where the wall of the nozzle is sufficiently thin as to have very little effect on aspiration efficiency. A more practical scenario of equivalent simplicity is the one involving a nozzle with finite wall thickness (a 'blunt' sampler) facing the wind.

Recently, there has been interest in studying the aspiration efficiencies  $A$  of aerosol samplers for a

\*To whom correspondence should be addressed. Department of Environmental Health Sciences, School of Public Health, University of Michigan, 109 S. Observatory, Ann Arbor, MI 48109-2039, USA. Tel: +1-734-936-0703; fax: +1-734-936-7283; e-mail: jhv@umich.edu

wider range of velocity ratio  $R$  (the ratio of the air velocity in the freestream,  $U$ , and that at the plane of the entry orifice,  $U_s$ ) than originally studied, including very high values of  $R$ . This was driven in part by the desire for new practical aerosol samplers to accurately sample according to specific health-related particle size-selective criteria at lower flowrates than previously, in order to facilitate the use of smaller, lighter sampling pumps for occupational hygiene applications. Early studies with practical samplers operated under such conditions revealed behaviors that were not consistent with trends that were expected on the basis of current knowledge of aerosol sampler theory. So, in a recent study to examine what happens in the simplest scenario under such conditions, Paik and Vincent (2002a) examined the limiting case of a thin-walled sampler facing the wind for  $R$ -values up to 50, greatly extending the range previously studied. The study showed that the classic model of Belyaev and Levin (1974), based on experimental data for aspiration efficiency at quite small  $R$ -values, progressively overestimated  $A$  for  $R$  greater than  $\sim 6$ . The original Belyaev and Levin model for thin-walled sampler aspiration efficiency was therefore modified to accommodate these larger  $R$ -values. As an extension of that simplest case, Paik and Vincent (2002b) examined the equivalent simple blunt sampler scenario for  $R$ -values (again) outside the range previously studied experimentally. Here, aspiration efficiency was studied for an axisymmetric disc-shaped sampler system facing the wind, with  $R$  from 0.5 to 25 and for particle aerodynamic diameter ( $d_{ae}$ ) ranging from 13 to 90  $\mu\text{m}$ . Results from this study also showed that, like the Belyaev and Levin model, the existing model (Vincent, 1987, 1989) for disc-shaped samplers overestimated  $A$ , this time for  $R$  greater than  $\sim 2$ . As in the thin-walled sampler study, the model was modified to accommodate larger  $R$ -values.

The current paper describes a further extension of those two relatively simple scenarios, to situations closer to what would be encountered during aerosol sampling in actual occupational hygiene situations. It describes aspiration efficiency uniformly averaged over all possible orientations with respect to the wind ( $A_{360}$ ), for a wide range of conditions defined by the three dimensionless groups of variables widely considered to be the most important (Vincent, 1989), following the general functional relationship

$$A_{360} = f\{St, R, r\} \quad (1)$$

in which  $St$  is the Stokes' number representing inertial forces, as given by

$$St = \frac{d_{ae}^2 \rho^* U}{18\eta\delta} \quad (2)$$

Here,  $d_{ae}$  is the particle aerodynamic diameter,  $\rho$  the density of water (corresponding to a unit-density sphere),  $\delta$  the diameter of the sampling inlet and  $\eta$  the viscosity of air. In addition, there is the ratio of geometric dimensions (the dimension ratio)

$$r = \delta/D \quad (3)$$

where  $D$  is the width of the sampler body (or, for personal samplers, the body on which the sampler is mounted). Finally, as already mentioned, there is the velocity ratio

$$R = U/U_s \quad (4)$$

Equation (1) provides the basis of a set of scaling laws by which the performances of aerosol samplers observed at large scale can be related to those for samplers observed at small scale. In turn, therefore, such scaling laws may underpin the application of small wind tunnels for research like that described here. Our two earlier investigations of thin-walled samplers and disc-shaped samplers (cited above) looked closely at the effects of  $St$ ,  $R$  and  $r$  for those simple systems. As useful as these studies were in increasing our collective understanding of aerosol sampling, aerosol sampling in the real world rarely occurs under such ideal conditions. So it was recognized that further research is needed towards bridging the gap between theory and reality. This therefore is the primary objective of the current work. It is expected that the new knowledge gained will be useful in designing and testing new aerosol samplers conforming to the inhalability curve.

## BACKGROUND

Over the years, a number of important studies have been conducted to establish the aspiration efficiency of the human head, i.e. the efficiency with which airborne particles may enter through the nose and the mouth of a human subject during breathing. The experimental studies in question were all carried out using life-sized, breathing mannequins in wind tunnels (Ogden and Birkett, 1977; Armbruster and Breuer, 1982; Vincent and Mark, 1982; Vincent *et al.*, 1990). These studies led to the development of the inhalability curve, which was eventually widely adopted as a criterion for the inhalable aerosol fraction (replacing what was previously referred to as 'total' aerosol) by many standards setting bodies (e.g. Soderholm, 1999; Vincent, 1999). A feature that is common to the inhalability convention that is now widely applied in occupational exposure standards is the assumption that the orientation of the human subject is uniformly averaged over all possible orientations. Although this was acknowledged from the outset to be an oversimplification with respect to

some working situations, it is recognized that the concept of orientation-averaging is the only satisfactory way to achieve a consistent definition that can be widely applied in the development and implementation of occupational aerosol exposure standards. The same philosophy has therefore been carried through widely to the assessment of the performances of personal aerosol samplers for the inhalable fraction which would be worn on the body of a worker. With this in mind, candidate samplers for the inhalable fraction have usually been tested while mounted on life-sized mannequins that in turn were rotated—either incrementally or slowly-continuously—about a vertical axis (Mark and Vincent, 1986; Kenny *et al.*, 1997). The research described in this paper reflects this same philosophy.

In order to avoid some of the difficulties associated with such experiments at full scale in large wind tunnels, alternative approaches have been sought for the development and testing of samplers involving experiments at smaller scale coupled with appropriate recognition of physical scaling relationships (Ramachandran *et al.*, 1998; Witschger *et al.*, 1998; Aizenberg *et al.*, 2000). It is especially relevant to note that Witschger *et al.* in particular suggested that the size of the bluff body (embodied in  $r$ , as described in this paper) might not be significant over certain ranges of  $r$ .

The new research described in this paper deals with one specific type of personal aerosol sampler for the inhalable fraction, the IOM personal inhalable aerosol sampler (SKC Ltd, Blandford Forum, Hants) and its derivatives. This instrument in its original form was developed in the 1980s during research at the Institute of Occupational Medicine (Edinburgh, UK)

(Mark and Vincent, 1986), and has become regarded as one suitable ‘reference’ sampler for the inhalable fraction (Bartley, 1998).

## MATERIALS AND METHODS

All the experiments described in this paper were carried out in our small wind tunnel at the University of Michigan (see Fig. 1). Aerosols were generated from the narrowly graded powders of fused alumina (Washington Mills Electromineral Company, Niagara Falls, NY) that have been widely used in the research of several different laboratories and whose physical characteristics as they relate to such research (i.e. particle size calibration) have been found to be very consistent. Different grades of these commercially available powder samplers provided aerosols with mass median  $d_{ae}$  in the range from 6 to 90  $\mu\text{m}$ , with geometric standard deviation generally less than  $\sim 1.30$ . Particulate material collected by test and reference samplers (in the form of isokinetic thin-walled probes) respectively were assessed gravimetrically. Orientation-averaged aspiration efficiency ( $A_{360}$ ) for the test samplers was obtained from the ratio of the concentration entering the test sampler to that entering the reference sampler. Full details of all the basic experimental procedures are given in an earlier paper (Paik and Vincent, 2002a).

For most of the experiments, the test samplers were mounted on a rectangular, three-dimensional bluff body, simulating the human body in real occupational hygiene situations. The bluff body was intended to reflect a simplified human torso. Its width-to-depth ratio was therefore set at 2, which was intentionally slightly higher than the chest width-to-depth ratio

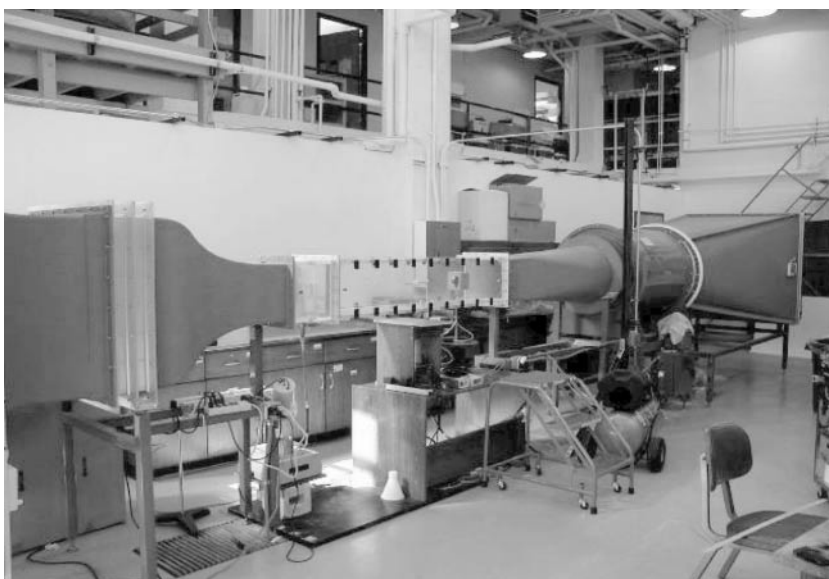


Fig. 1. Small wind tunnel.

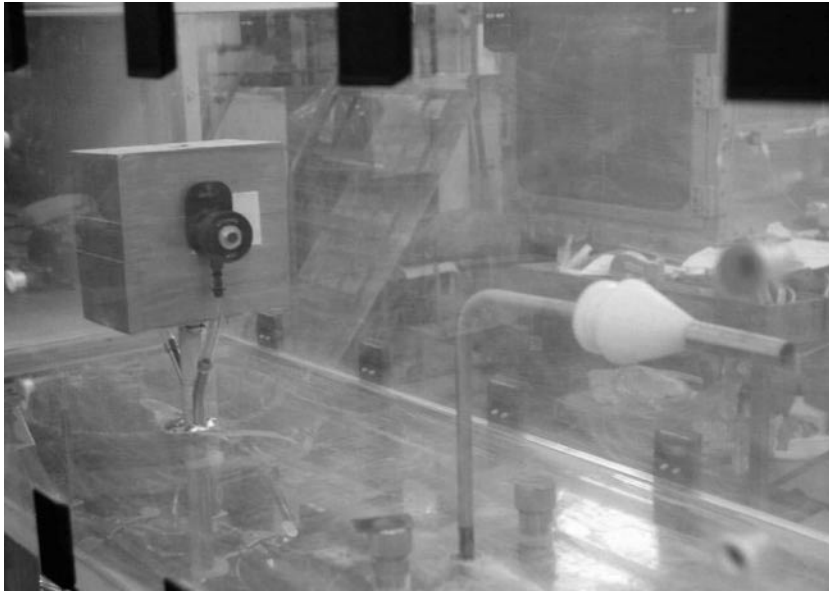


Fig. 2. Bluff body with sampler and isokinetic sampler.

determined from anthropomorphic data, in order to account for the arms. For most of the experiments, its width and depth were 120 and 60 mm, respectively, and its height was arbitrarily set equal to its width. For some experiments, however, a smaller bluff body was also used, and for this the width and depth were 75 and 37.5 mm, respectively. To investigate  $A_{360}$ , IOM-like samplers were mounted on one or both sides of the bluff body, as shown in Fig. 2. In Fig. 2, a version of the IOM sampler is shown with a modified inlet in the form of an insert placed inside the original inlet to reduce the inlet diameter. Also shown is the upstream reference sampler that was used, taking the form of a thin-walled cylindrical operated isokinetically (where the white conical shroud served to contain the collection filter while minimizing the aerodynamic interference with the air flow around the probe). In order to achieve orientation-averaging, the bluff body was rotated slowly at a constant rate of  $\sim 2$  r.p.m. For the sake of simplicity, the samplers were mounted centrally on the bluff body. While personal samplers are usually asymmetrically located on the bodies of workers in practical occupational hygiene sampling situations, it has been shown that positional effects associated with the placement of samplers on mannequins are small (Kenny *et al.*, 1997). Similar assumptions were made in other laboratory studies of personal samplers (e.g. Witschger *et al.*, 1998; Aizenberg *et al.*, 2000).

Since the goal of the current experiments was first to determine how blunt samplers would perform in realistic field situations, and then to use that knowledge as a basis for developing new samplers,  $A_{360}$  for IOM samplers, under various conditions, was exam-

ined experimentally. IOM samplers were chosen because of their simple geometries and because they incorporated cassettes that were capable of collecting all the particles that entered into their orifices. Thus, the performance of this instrument is determined specifically by its aspiration efficiency.

In the first set of experiments,  $A_{360}$  was determined for wide ranges of  $R$  and  $St$ , and for two values of  $r$ . Two samplers were tested simultaneously, one on the front and the other on the back of the bluff body. One sampler was the original IOM sampler with its 15 mm orifice, the other had a modified inlet of diameter 7.9 mm (see Fig. 2). In this way, two samplers, characterized by two different  $r$ -values, could be tested simultaneously. Since  $U$  was kept constant at 1 m/s,  $R$  was varied by changing the sampling flowrate, providing an  $R$ -range of 2–15. Based on the different particle sizes and inlet sizes that were investigated,  $St$  ranged from 0.03 to 3.08, and the two inlet diameters provided  $r$ -values of 0.125 and 0.066, respectively. Three repeats were obtained for each combination of  $St$ ,  $R$  and  $r$ .

For the second set of experiments, two bluff bodies were employed to allow a wider range of  $r$ , with widths 120 and 75 mm, respectively. For these studies, however, both were modified so that the test samplers could be recessed somewhat. This was done in order to avoid having the samplers project excessively from the simulated worker's torso relative to the size of the torso (which would become more marked for the smaller bluff body). In addition to mounting the samplers on the two bluff bodies, experiments were also conducted for the IOM sampler mounted alone in isolation. Here it is noted

that the width of the sampler body corresponding to  $D$  in equation (3) was 37 mm. For these experiments, the unmodified IOM sampler (with  $\delta = 15$  mm) was chosen. The velocity ratio,  $R$ , was held constant at 5.3, approximately corresponding to the IOM sampler operating at 2 l/min at a windspeed of 1 m/s. With this system,  $r$ -values of 0.125, 0.2 and 0.4 were achieved. Again, as in the first set of experiments, experiments were carried out for three particle sizes. This time, however, the smallest particle size we used was 6  $\mu\text{m}$ , corresponding to a  $St$ -value of 0.007.

## RESULTS

### *Orientation-averaged aspiration efficiency ( $A_{360}$ ) as a function of velocity ratio ( $R$ ) and Stokes' number ( $St$ )*

In the expectation that they might be useful to other researchers, the full experimental results for  $A_{360}$  as a function of  $R$  and  $St$  are shown in Table 1. They are also displayed in graphical form in Fig. 3a–c. The reproducibility of the data is generally good, with an overall average relative standard deviation (RSD) of <10%. This was not quite as good as that obtained from the earlier thin-walled sampler and disc-shaped sampler studies, where the overall average RSD for repeated measurements was ~5% (Paik and Vincent, 2002a,b). Here it was clear that more variability was introduced by rotating the samplers. All sample masses exceeded the limit of quantitation of 0.67 mg, which was determined from a separate evaluation of

the gravimetric analysis method used (Paik and Vincent, 2002c).

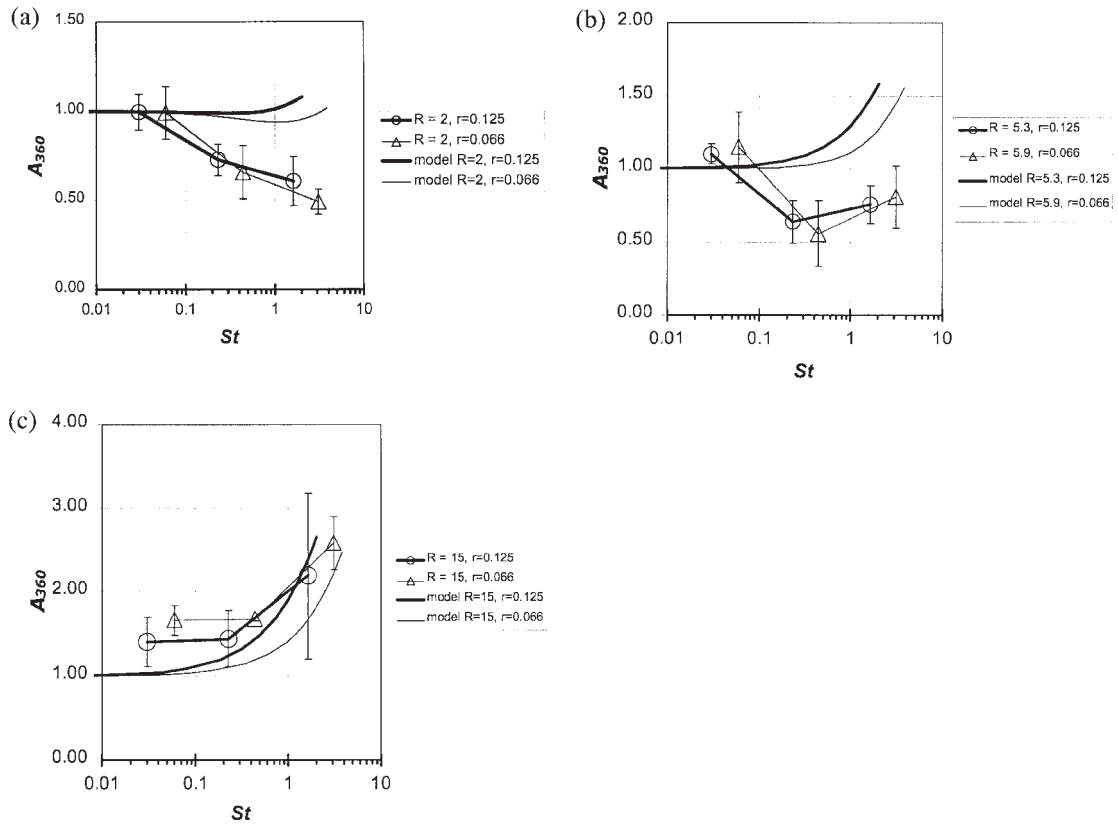
In order to determine the relative influences of  $R$ ,  $St$  and  $r$  on  $A_{360}$ , a general linear model (GLM) routine from SPSS® (SPSS Science, Chicago, IL) was used. While the effects of these variables may not be completely linear, the GLM routine was chosen to provide a rough approximation of the relative effects of these three variables on  $A_{360}$ . The analysis showed that  $R$  had by far the greatest linear influence on  $A_{360}$ , with a  $P$ -value <0.05. The  $P$ -values obtained for  $St$  and  $r$  were 0.202 and 0.709, respectively. To compare the relative effects of  $St$  and  $r$ , the GLM routine was repeated, this time for  $St$  and  $r$  at each  $R$ -value. For  $R = 2$  and 15,  $St$  was shown to have a statistically significant linear effect on  $A_{360}$  ( $P < 0.05$ ). But for  $R \approx 5.5$ ,  $St$  was not shown to have a significant linear effect. No linear effects were observed for  $r$  for any of the combinations of  $R$  and  $St$  tested (at the 95% confidence level). In addition, a paired  $t$ -test was conducted using SPSS® to compare the mean  $A_{360}$ -values for  $r = 0.125$  and 0.067, under similar  $St$  and  $R$  conditions. This analysis also indicated no statistically significant differences ( $P > 0.05$ ).

### *Orientation-averaged aspiration efficiency ( $A_{360}$ ) as a function of dimension ratio ( $r$ )*

The experimental results from the second set of experiments are shown in Table 2 and Fig. 4. Since we were mainly concerned with the effects of  $r$  on  $A_{360}$ , a one-way ANOVA was performed to compare

Table 1. Experimental values of  $A_{360}$  for experiment 1

$d_{ac}$ ( $\mu\text{m}$ )	$\delta$ (mm)	$D$ (mm)	$r$	$Q$ (l/min)	$R$	$St$	$A_{360}$
13	7.9	120	0.066	1.47	2.0	0.06	0.98, 0.92, 1.07
13				0.50	5.9	0.06	1.29, 1.07, 1.08
13				0.20	15	0.06	1.76, 1.73, 1.49
34				1.47	2.0	0.44	0.64, 0.59, 0.74
34				0.50	5.9	0.44	0.43, 0.65, 0.59
34				0.20	15	0.44	1.67, 1.84, 1.50
89.5				1.47	2.0	3.08	0.52, 0.45, 0.50
89.5				0.50	5.9	3.08	0.86, 0.88, 0.68
89.5				0.20	15	3.08	3.15, 2.39, 2.20
13	15	120	0.125	5.3	2.0	0.03	0.98, 0.95, 1.05
13				2.0	5.3	0.23	1.13, 1.11, 1.06
13				0.71	15	1.62	1.49, 1.41, 1.31
34				5.3	2.0	0.03	0.77, 0.68, 0.73
34				2.0	5.3	0.23	0.58, 0.72, 0.61
34				0.71	15	1.62	1.45, 1.43, 1.44
89.5				5.3	2.0	0.03	0.68, 0.54, 0.60
89.5				2.0	5.3	0.23	0.82, 0.69, 0.75
89.5				0.71	15	1.62	2.38, 2.09, 2.10



**Fig. 3.** (a)  $A_{360}$  as a function of  $St$ , for  $R = 2$ . (b)  $A_{360}$ , as a function of  $St$ , for  $R = 5.3$  and  $5.9$ . (c)  $A_{360}$  as a function of  $St$ , for  $R = 15$ . Error bars represent 95% confidence intervals derived from the repeated measurements. Model predictions are based on the Paik and Vincent (2002b) model for disc-shaped samplers facing the wind.

Table 2. Experimental values of  $A_{360}$  for experiment 2

$d_{ac}$ ( $\mu\text{m}$ )	$Q$ (l/min)	$R$	$\delta$ (mm)	$D$ (mm)	$r$	$St$	$A_{360}$
6	2	5.3	15	120	0.125	0.007	1.01, 1.02, 1.01, 1.02
6				75	0.2	0.007	1.02, 1.03, 1.03, 1.05
6				37	0.4	0.007	0.99, 0.98, 0.99, 1.00
34				120	0.125	0.23	0.60, 0.62, 0.66, 0.66
34				75	0.2	0.23	0.61, 0.57, 0.66, 0.67
34				37	0.4	0.23	0.57, 0.57, 0.69, 0.65
89.5				120	0.125	1.62	0.75, 0.82, 0.68, 0.70
89.5				75	0.2	1.62	0.67, 0.78, 0.60, 0.58
89.5				37	0.4	1.62	0.64, 0.64, 0.71, 0.73

the mean  $A_{360}$ -values obtained for the three  $r$ -values. The one-way ANOVA indicated that there were no statistically significant differences in the mean  $A_{360}$ -values obtained for  $r = 0.125$ ,  $0.20$  and  $0.40$ , for  $St$ -values of  $0.23$  and  $1.62$ , respectively ( $P > 0.05$ ). However, statistically significant differences in the mean  $A_{360}$ -values were found for the smallest  $St$ -value of  $0.007$ .

To compare how the IOM sampler performed against the inhalability curve, Fig. 5 presents the same results, this time expressing  $A_{360}$  as a function of  $d_{ac}$  (consistent with how the inhalability convention is defined). No statistical tests were performed for this comparison; however, a visual inspection of the graph shows that our data are reasonably close in proximity to the inhalability curve.

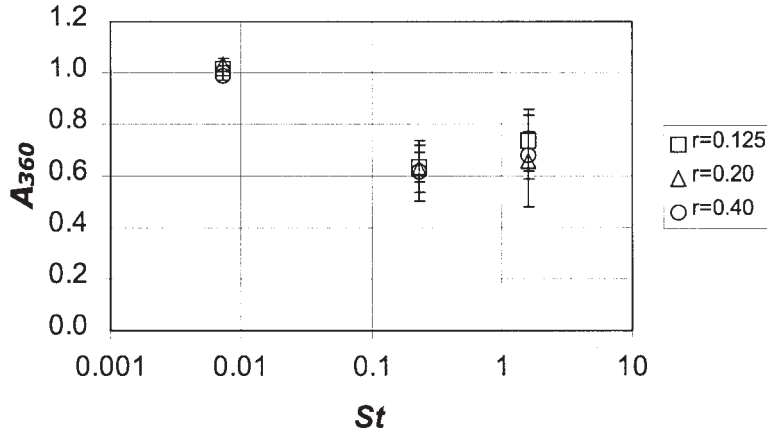


Fig. 4.  $A_{360}$  as a function of  $St$ , for various  $r$ -values.

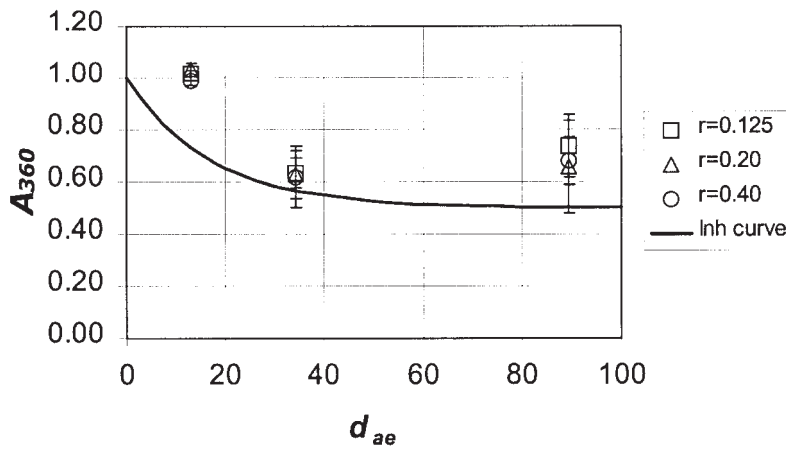


Fig. 5.  $A_{360}$  as a function of  $d_{ae}$ , for various  $r$ -values: squares represent data for  $r = 0.125$ , triangles for  $r = 0.2$ , and circles for  $r = 0.4$ . The solid line represents the conventional inhalability curve.

## DISCUSSION

*Orientation-averaged aspiration efficiency ( $A_{360}$ ) as a function of velocity ratio ( $R$ ) and Stokes' number ( $St$ )*

One of the goals of this study was to see how the performances of blunt aerosol samplers would change if they were placed at orientations with respect to the wind that were averaged over  $360^\circ$ , as opposed to when they were facing the wind (especially for large  $R$ -values). In order to make this comparison, predicted values of aspiration efficiency from the improved model in the earlier study of simple blunt samplers facing the wind (Paik and Vincent, 2002b) were compared with the current experimental data, for equivalent values of  $St$ ,  $R$  and  $r$ . The comparison was made under the assumption that the different shapes of the samplers (where the bluff body was regarded as part of the sampler body in the case of the

IOM sampler) would only account for small differences in aspiration efficiency, compared to the more dominant effects of  $R$  and  $St$ , and possibly  $r$ . Although the experimental (orientation-averaged) and predicted (forwards-facing) scenarios are quite different, the comparison is expected to highlight some important characteristics of orientation-averaged sampling.

Figure 3a for  $R = 2$  clearly shows that the experimentally measured  $A_{360}$  decreases with increasing  $St$ . The same trend had been observed in the earlier inhalability studies, and is due to the reduced ability of large particles to follow the complex air motions near the sampler as it is rotated through different orientations with respect to the wind. For  $R \approx 5$  (see Fig. 3b),  $A_{360}$  initially decreases with increasing  $St$ , but then increases for the largest  $St$ -value. This was supported by the results of two-sample  $t$ -tests (again, using SPSS®) that compared mean  $A_{360}$ -values obtained for the  $St$ -values tested. Statistically signifi-

cant differences ( $P < 0.05$ ) in mean  $A_{360}$  were found for  $St$ -values of 0.03 to 0.06 versus 0.23 to 0.44, and 0.23 to 0.44 versus 1.62 to 3.08, reflecting a significant fall followed by a rise in  $A_{360}$ . (For simplicity, the  $St$ -values were divided into three groups for the  $t$ -tests. Each group consisted of the two  $St$ -values obtained for each particle size.) Armbruster and Breuer (1982) and Vincent *et al.* (1990) had observed such a trend at high windspeeds (similarly corresponding to  $R$ -values around 5) during their studies of the aspiration efficiency of the human head. Also, a comparison of the model predictions and measured  $A_{360}$  data clearly show the strong influence of aspiration efficiency for forwards-facing on  $A_{360}$ .

For  $R = 15$  (see Fig. 3c), the measured  $A_{360}$  increases with increasing  $St$ . Here, the experimental results are very close to the predicted aspiration efficiency for forwards-facing. This shows that at very high  $R$ -values,  $R$  is the predominant factor in determining sampler performance, and that aspiration efficiency is dominated by the contribution to its orientation-averaged value from the forwards-facing part. This opens up the possibility of defining a threshold value of  $R$  above which the performances of samplers are not significantly affected by sampler orientation, and they can be predicted by simple models such as the one developed for disc-shaped samplers facing the wind. Some unexpected biases were observed, however, for  $St = 0.03$  to 0.44. Over this range,  $A_{360}$  was actually greater than the value predicted for forwards-facing. The projection of the sampler outwards from the bluff body in the first series of experiments may have been partly responsible for this bias. A comparison of Fig. 3b and Fig. 4 (both of which show data for  $A_{360}$  obtained at  $R \approx 5$ ) shows that, once the sampler was recessed into the bluff body (as in the second series of experiments), such effects were much reduced.

For the very limited range of  $r$  tested in these particular experiments, the GLM analyses and additional paired  $t$ -tests showed that there were no statistically significant differences in  $A_{360}$  ( $P > 0.05$ ) for the two  $r$ -values, which confirmed the tendency noted in our previous blunt sampler study (Paik and Vincent, 2002b). However, it is not yet known whether this tendency applies to a wider range of  $r$ .

#### *Orientation-averaged aspiration efficiency ( $A_{360}$ ) as a function of dimension ratio ( $r$ )*

In order to examine the effect of  $r$ , one-way ANOVA was used to compare the  $A_{360}$ -values of the three samplers at each particle size (corresponding to  $St$ -values of 0.007, 0.23, and 1.62) at the 95% confidence level. While there were no statistically significant differences in mean  $A_{360}$  for the three  $r$ -values examined for  $St = 0.23$  and 1.62, statistically significant differences were found for  $St = 0.007$ . This was very surprising because it is expected that  $r$ -effects

should be less significant at low  $St$ -values, due to the low-inertia particles' ability to follow streamlines, regardless of the airflow distortion associated with the bluff body. Based on this understanding, the statistical data obtained for  $St = 0.007$  were considered anomalous and attributed to the small sample size and very small variability which was found for these particles. Conversely, the data obtained for the larger  $St$ -values were considered more indicative of the  $r$ -effect on  $A_{360}$ .

We therefore concluded that, overall, there were no statistically significant differences in the performances of the IOM samplers for sampling systems with  $r$  over the range from 0.125 to 0.4. Combined with what was learned from the first set of experiments, this range can be extended to  $r = 0.066$  to 0.4. In practical terms, a low  $r$ -value of 0.066 corresponds approximately to an IOM sampler mounted on a 230 mm wide bluff body, which is about one-half to two-thirds the width of a typical life-size mannequin. At the other end of the range, an  $r$ -value of 0.4 would correspond to an IOM sampler placed alone and in isolation. By showing no differences in performance for such different sampling configurations, it was confirmed that the IOM sampler collects the inhalable aerosol fraction even when used as a stand-alone sampler. This is a surprising result, contradicting the previous expectation (by aerosol scientists) that the role of the bluff body of the wearer of a personal sampler should significantly influence the performance of the sampler.

It is also noted in Fig. 5 that, for the windspeed of 1 m/s chosen for these experiments,  $A_{360}$  rises above the inhalability curve at the largest particle size studied. Such a tendency has previously been observed, as noted in above, and as observed in the Kenny *et al.* (1997) study.

## CONCLUDING REMARKS

In this paper we have described two sets of experiments to investigate the orientation-averaged aspiration efficiencies of small aerosol samplers mounted on bluff bodies (representative of the wearing of personal samplers by workers in occupational hygiene exposure assessment scenarios). This idealized scenario was chosen because of its relevance to inhalable aerosol sampling in relation to the convention for the inhalable aerosol fraction that underlies many current aerosol exposure standards. The first set of experiments addressed the relationships between  $A_{360}$  and (mainly)  $St$  and  $R$ , respectively. The second set of experiments addressed the role of  $r$ . Overall it was shown that both  $St$  and  $R$  are by far the most strongly influential factors. In general, the effect of  $R$  was greatest at large  $St$ , and the effect of  $St$  was greatest for large  $R$ . That is, the effect of changing windspeed is greatest for the largest particles, and the

effect of changing the particle size is greatest for the highest windspeed. Both  $R$  and  $St$ , therefore, are complementary in their effects on  $A_{360}$ , confirming what was found in our earlier studies of thin-walled and blunt samplers facing the wind (Paik and Vincent, 2002a,b). It was interesting to note that, at high  $R$  (reflecting high windspeed and/or low sampling flowrate),  $A_{360}$  is strongly influenced by the contribution when the sampler is facing into the wind.

The minimal observed effect of  $r$  on  $A$  for the orientation-averaged sampling scenarios described in this paper raises intriguing questions about the role of bluff bodies in testing personal samplers. It points towards the idea that, for testing aerosol samplers, it may not—after all—be necessary for the samplers to be tested while mounted on a mannequin or some representative bluff body. Indeed, it may even go so far as to suggest that samplers may be tested alone and in isolation. If that is indeed the case, then future protocols for testing and evaluating personal aerosol samplers may involve much simpler experiment systems than heretofore envisaged. However, while  $r$ -effects were not observed for  $r$  as low as 0.066, an  $r$ -value of 0.035 is more representative of workers wearing IOM samplers. Also, although we evaluated  $R$ -values ranging from 2 to 15, much smaller  $R$ -values may be associated with many workplaces and for other aerosol samplers (with different sampling flow rates). Therefore there is a need for additional studies to address these questions. There is an additional caution. Results like those described in this paper should not be taken to support the suggestion that personal sampling is not required for occupational aerosol exposure assessments. Such an idea might be an attractive possibility, since personal sampling—involving actual workers—is time-consuming and (often) logistically difficult and inconvenient. However, apart from the part size-selective performances of such aerosol samplers, as addressed in this paper, it is important to remember that, based on the results from many occupational hygiene studies in the field, the intensity of exposure as measured with personal samplers has frequently been found to be greater than that estimated from static or area measurements.

In summary, based on what was learned from our experiments, we conclude that a foundation exists for the development and testing of new prototype aerosol samplers using simplified testing protocols.

*Acknowledgements*—The authors wish to thank CDC-NIOSH for its support of this work under grant no. 5-RO1-OH0387-03.

## REFERENCES

- Aizenberg V, Grinshpun SA, Willeke K, Smith J, Baron PA. (2000) Measurement of the sampling efficiency of personal inhalable aerosol samplers using a simplified protocol. *J Aerosol Sci*; 31: 169–79.
- Armbruster L, Breuer H. (1982) Investigations into defining inhalable dust. *Ann Occup Hyg*; 26: 21–32.
- Bartley DL. (1998) Inhalable aerosol samplers. *Appl Occup Environ Hyg*; 13: 274–8.
- Belyaev SP, Levin LM. (1974) Techniques for collection of representative aerosol samples. *J Aerosol Sci*; 5: 325–38.
- Kenny LC, Aitken RJ, Chalmers C, *et al.* (1997) A collaborative European study of personal inhalable aerosol sampler performance. *Ann Occup Hyg*; 41: 135–53.
- Mark D, Vincent JH. (1986) A new personal sampler for airborne total dust in workplaces. *Ann Occup Hyg*; 30: 89–102.
- Ogden TL, Birkett JL. (1977) The human head as a dust sampler. In Walton WH, editor. *Inhaled Particles IV*. Oxford: Pergamon Press. pp. 93–105.
- Paik SY, Vincent JH. (2002a) Aspiration efficiency of thin-walled nozzles facing the wind and for very high velocity ratios. *J Aerosol Sci*; 33: 705–20.
- Paik SY, Vincent JH. (2002b) The aspiration efficiency for disc-shaped nozzles facing the wind, for coarse particles and high velocity ratios. *J Aerosol Sci*; 33: 1509–23.
- Paik SY, Vincent JH. (2002c) Filter and cassette mass instability in ascertaining the limit of detection of inhalable airborne particulates. *Am Ind Hyg Assoc J*; 63: 698–702.
- Ramachandran G, Sreenath A, Vincent JH. (1998) Towards a new method for experimental determination of aerosol sampler aspiration efficiency in small wind tunnels. *J Aerosol Sci*; 29: 875–91.
- Soderholm SC. (1999) Proposed international conventions for particle size-selective sampling. *Ann Occup Hyg*; 33: 301–21.
- Vincent JH. (1987) Recent advances in aspiration theory for thin-walled and blunt aerosol sampling probes. *J Aerosol Sci*; 18: 487–98.
- Vincent JH. (1989) *Aerosol sampling: science and practice*. Chichester: John Wiley.
- Vincent JH. (editor) (1999) *Particle size-selective sampling for particulate air contaminants*. Cincinnati, OH: American Conference of Governmental Hygienists.
- Vincent JH, Mark D. (1982) Applications of blunt sampler theory to the definition and measurement of inhalable dust. *Ann Occup Hyg*; 26: 3–19.
- Vincent JH, Mark D, Miller BG, Armbruster L, Ogden TL. (1990) Aerosol inhalability at higher windspeeds. *J Aerosol Sci*; 21: 577–86.
- Witschger O, Willeke K, Grinshpun SA, Aizenberg V, Smith J, Baron PA. (1998) Simplified method for testing personal inhalable aerosol samplers. *J Aerosol Sci*; 29: 855–74.