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Aspiration and sampling efficiencies of the TSP and louvered particulate matter inlets†

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An experimental system was developed for the rapid measurement of the aspiration/transfer efficiency of aerosol samplers in a wind tunnel. We attempted to measure the aspiration and particle transfer characteristics of two inlets commonly used for sampling airborne Particulate Matter (PM): the 'Total Suspended Particulate' or TSP inlet, and the louvered 'dichotomous sampler inlet' typically used in sampling PM10 or PM2.5. We were able to determine the fraction of the external aerosol that enters the inlet and is transferred through it, and hence is available for collection by a filter, or further size fractionation into PM10 or PM2.5. This 'sampling efficiency' was analysed as a function of dimensionless aerodynamic parameters in order to understand the factors governing inlet performance. We found that for the louvered inlet the sampling efficiency increases as the external wind increases. Under all conditions expected in practical use the louvered inlet aspirates sufficient PM to allow either PM10 or PM2.5 to be selected downstream. The TSP inlet's sampling efficiency decreases with increasing external wind, and the TSP inlet is likely to under-sample the coarse end of the PM10 fraction at moderate and high external winds. As this inlet is generally not used with a downstream size fractionator, changes in sampling efficiency directly affect the measured aerosol concentration. We also investigated whether it is possible to dimensionally scale the PM inlets to operate at either higher or lower flow rates, while preserving the same sampling characteristics as the current full-scale, 16.67 L min^{-1} (L m^3 h^{-1}) versions. In the case of the louvered inlet, our results indicate that scaling to lower flow rates is possible; scaling to higher flow rates was not tested. For the TSP sampler, the sampling efficiency changes if the sampler is scaled to operate at smaller or larger flow rates, leading to unreliable performance.

Aims of the investigation

Wind tunnel testing of aerosol sampling inlets is rarely carried out owing to high cost and technical complexity. Wind tunnel test procedures typically involve repeat experiments with monodisperse aerosols spanning a range of sizes, plus repeats at different wind speeds, in order to fully characterise the inlet or the sampling efficiency. For example, the USEPA laboratory procedure for testing a PM10 reference inlet, described in the US Federal Register (40CFR Part 53),[1] requires the inlet to be tested with 10 different monodisperse aerosols at each of three wind speeds. The test aerosols are required to be generated as fluorescently-tagged droplets, each aerosol requiring careful calibration of particle size as well as close attention to spatial and temporal homogeneity in the wind tunnel. Analysis of collected aerosol fractions requires careful and prolonged laboratory procedures. Executing the complete test sequence could easily take the experienced researcher several months. Test facilities with the equipment and expertise to carry out this work are very few in number. In effect, the high cost involved has tended to stifle innovation in the design of new ambient PM inlets.

Recognition of this problem has led to efforts to develop new, rapid procedures for characterising aerosol inlets and samplers. Major time savings can be obtained with test methods using polydisperse aerosols, in effect enabling the entire particle size dependence to be measured in a single experiment.[2] These methods have been successfully applied by many experimenters to the characterisation of samplers in calm air, or in slowly-moving air streams. Ramachandran *et al.*[3] proposed the application of dimensional scaling principles to particle aerodynamic behaviour, to enable testing sampling inlets on small scales or enlarged scales. Polydisperse test methods applied on arbitrary scales would, if technically feasible, enable rapid wind tunnel testing to contribute to an iterative design process for new aerosol sampling systems. Anticipated future needs for new PM instruments include the development of low-flow monitors capable of extended remote operation, or alternatively high-flow monitors able to give better analytical sensitivity for particle chemistry.

In this paper we describe efforts to implement a wind tunnel testing system for aerosol inlets that facilitates rapid characterisation through the use of polydisperse aerosols and time-of-flight methods. We utilised the system to test two inlets commonly used for sampling airborne PM: the 'Total Suspended Particulate' or TSP inlet, and the low-volume louvered 'dichotomous' sampler inlet typically used in monitoring PM10 or PM2.5. By conducting tests on these inlets at different scales we have explored the feasibility of dimensional scaling in wind tunnel tests, and also investigated whether existing inlet designs can be used as a basis for samplers operating at different flow rates.

The TSP inlet is an omni-directional inlet that is widely used for general particulate pollution monitoring. Versions are available for both high volume and low volume air pollution monitors. The low volume (16.67 L min^{-1}) units tested here were originally developed without any systematic testing, as an "intelligent rain cap". Very few data on the particle-size-resolved sampling efficiency under various wind conditions

† Electronic supplementary information (ESI) available: plots of efficiency data *versus* Stokes number for the two inlet types (Fig. 8 and 9). See http://www.rsc.org/suppdata/em/b4/b419001g/

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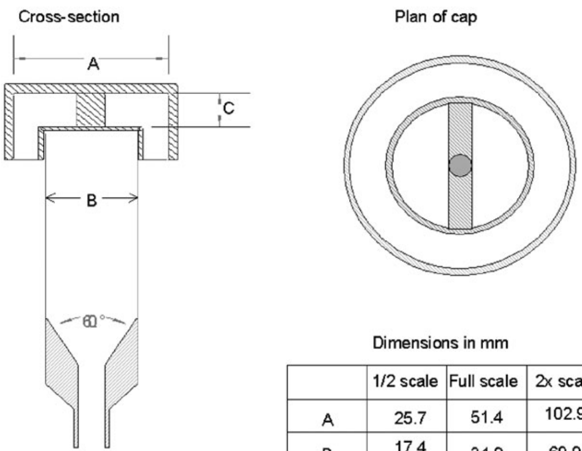
are available from the literature; for the low-volume TSP inlet there are no published data. The low-volume TSP inlet fits over a 1.25 inch diameter downtube, operated with inlet flow rate 16.67 L min^{-1}. The dimensions of the cap are such that the inlet velocity, through the upward facing annular inlet, is similar to the sedimentation velocity of 100 μm particles in calm air (24.8 cm sec^{-1}). The TSP inlet is thus assumed to collect particles with a wide spectrum of sizes up to around 30–40 μm, although it has never been subjected to rigorous testing to confirm its performance.

The louvered dichotomous inlet has found widespread application in the US and Europe for low-volume or continuous pollution monitoring. The inlet was developed as a 'next generation' inlet to the TSP, and its main purpose is to select particles from the external moving air stream and to transmit these particles to a downstream impactor in order to separate the PM10 fraction. Various designs of the inlet have been subjected to rigorous testing,[4] although this was nearly always as a combined unit with the PM10 impactor in place. Hence detailed data on the aspiration or sampling efficiency of the inlet itself, as a function of particle size and wind speed, are not available. There are limited published data on the sampling characteristics of the inlet, without impactor, in calm air.[5]

Experimental methods

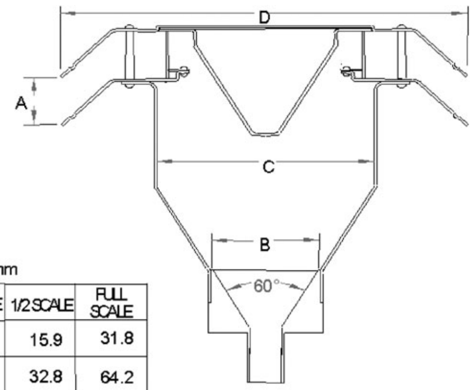
For the TSP inlet, a commercially-available full-scale inlet was purchased and double-scale and half-scale replicas were manufactured for this project by BGI Inc. A schematic diagram of the three TSP inlets with relevant dimensions is shown in Fig. 1. The full-scale louvered inlet was purchased from BGI Inc. The half-scale and third-scale replicas of this inlet were adapted from replica small-scale dichotomous inlets (of a slightly older design) already used at one partner laboratory (HSL) for previous work; these small-scale inlets had been originally manufactured by Rupprecht and Patashnick Inc. They were modified by BGI Inc. to attach new small-scale louvered inlet plates to the entry, making them as similar as practicable to the current full-scale version. A schematic diagram with dimensions is shown in Fig. 2. Note that due to the complex geometry of the louvered inlet, precise scaling of all features was not possible. For example the stand-offs separating the inlet plates could not be fully scaled down as this would have made it difficult to cut the internal screw threads that allow the pieces to be joined. It was also not possible to scale down the insect screen that is normally used to protect the inlet of the louvered inlet when used outdoors, so all three louvered inlets were tested without insect screens in place (which may affect results).



Dimensions in mm

	1/2 scale	Full scale	2x scale
A	25.7	51.4	102.9
B	17.4	34.9	69.9
C	6.4	12.7	25.4

Fig. 1 Schematic diagram of the TSP inlets.



Dimensions in mm

	1/3 SCALE	1/2 SCALE	FULL SCALE
A	10.7	15.9	31.8
B	22.2	32.8	64.2
C	43.7	65.8	132.1
D	82.6	111.8	246.4

Fig. 2 Schematic diagram of the louvered inlets.

The louvered inlets were also tested without any PM10 impaction system in place.

Reference inlets were required for isokinetic sampling of the reference wind tunnel concentration in each experiment. In general the flow rate used for the reference measurement was identical to the flow rate in the test measurement, meaning that each experiment required its own reference inlet, designed to have an inlet velocity equal to the external tunnel velocity, at the required flow rate. Reference probe dimensions for each experiment were calculated and are given in the experimental scheme in Table 1.

The testing scheme, summarised in Table 1, utilised wind tunnels of varying size and specification at each of the four partner laboratories (HCL, FHG, LU and IOM), the experimental work being distributed between wind tunnels so as to keep the blockage below 10% at all times. Blockage is defined as the proportion of area in the plane of the test section that is occluded by the test object. HSL, LU and FHG all used a polydisperse test aerosol of glass microspheres (particle density 2.45 g cc^{-1}) with sensing by the TSI Inc. Aerodynamic Particle Sizer (APS) for their measurements. In the much larger wind tunnel at IOM, narrow-fraction aloxite test aerosols with mass median aerodynamic diameters of 13, 26, 46 and 74 μm were used, followed by gravimetric analysis of both reference and test samples. Details of both experimental methodologies have been described in a number of other publications.[6,7] The wind tunnels used generally had an upper wind speed operational limit of 6–7 m s^{-1}, and lower wind speed of 0.5 m s^{-1}, which set limits on the experimental design.

Isokinetic sampling in the wind tunnel requires the reference probe to be forward facing, in alignment with the wind direction. The inlet to the APS is on the top of the instrument, and the delicate optics and electronics make it unwise to locate the APS inside a dust-laden wind tunnel. Hence to connect a forward-facing isokinetic reference probe to an APS located below the wind tunnel working section, a connecting tube is used that incorporates a 90 degree bend (see schematic diagram in Fig. 3). Normally, the TSP and louvered samplers are used upright as shown in Fig. 3, and can therefore be connected to the APS without a bend. However utilising the test system in this way could lead to systematic errors, since particle transfer losses in the reference and test-sampler connection lines may differ. Preliminary experiments were required therefore to investigate the magnitude of particle transmission losses in the system, and to develop a method for either eliminating or correcting for any differential losses.

Table 1 Experimental plan for the wind tunnel tests

Inlet	Flow rate/ L min^{-1}	Inlet velocity/ m s^{-1}	Wind speed/ m s^{-1}	Reference probe diameter/mm	Test carried out by HSL	LU	FHG	IOM
TSP full scale	16.7	0.28	1	18.8	x	x	x	x (1 size)
TSP full scale	16.7	0.28	2	13.3	x	x	x	x (1 size)
TSP half scale	8.35	0.56	2	9.4	x		x	
TSP half scale	8.35	0.56	4	6.6	x		x	
TSP double scale	33.4	0.14	0.5	37.6	x		x	
TSP double scale	33.4	0.14	1	26.6	x		x	
Louvered full scale	16.7	0.34	1	18.8		x		x (3 sizes)
Louvered full scale	16.7	0.34	0.5	26.6		x		x (3 sizes)
Louvered half scale	8.35	0.69	2	9.4	x	x	x	
Louvered half scale	8.35	0.69	1	13.3	x	x	x	
Louvered third scale	5.57	1.03	3	6.3	x	x	x	
Louvered third scale	5.57	1.03	1.5	8.9	x	x	x	

Determination of particle losses in the test system

Consider the connections of an arbitrary sampler S, and reference probe R, to the APS *via* a bend B and straight pipe P, as shown schematically in Fig. 3. The test condition has external wind speed W and the flow rate through the system is Q. Ideally we would like to determine the aspiration efficiency of the sampler S by comparing the aerosol number distributions sampled alternately through S and R. However, each sample will be subject to losses in S, R, B and P. The aspiration efficiency of S can only be measured without systematic error if the losses within S and R are negligible, and the losses in B and P are identical. Where these conditions cannot be met an alternative option is to determine all losses as a function of particle size, and to correct the APS data accordingly. A number of experiments were carried out to assess the losses in S, R and B, and to evaluate how losses depend on the dimensions of R and other governing variables (Q, W). Extensive previous work using the APS system in calm air had already shown losses in a straight pipe P to be negligible for glass particles over the size range of interest to this experiment.[2]

Reference inlet and bend transmission

Two methods were used to determine losses in R and B. The reference system was used with a filter downstream of the bend B, to sample an aerosol of aloxite F800 from the wind tunnel. When dispersed, this material has a mass median aerodynamic diameter of 12 µm, GSD around 1.4, and more than 95% of particle mass contained in particles with aerodynamic diameters below 20 µm, which is well within the APS range. The particles depositing in the reference inlet R, the bend B and the downstream filter were quantified separately, using a washing technique to remove particles from the tubes onto a preweighed filter. The results are shown in Fig. 4. These show that the reference inlet losses are very low in comparison to the bend losses. Total losses do not appear to depend strongly on flow rate.

The second method to assess losses also used the filter technique as described above, but allowed the size dependence to be measured in addition to the total loss. Tests were carried out with the polydisperse glass aerosol that was later used to test sampling efficiency, collecting separately the fraction of glass aerosol depositing in ($R + B$) and that passing through to the filter. Note that this test aerosol contained significant particle mass in particle sizes well above the range of the APS. The wall losses were washed into suspension using filtered electrolytic solution and prepared for size analysis using an Electrozone counting method (Coulter™ Multisizer) to measure the particle volume diameter distribution. Analysis was carried out using an orifice diameter of 100 µm, allowing detection of the majority of particle sizes present in the glass aerosol. By comparing the size distributions of the 'inlet loss' samples and the 'filter deposit' samples, it was possible to calculate the transmission of several individual 'inlet + bend' combinations as a function of particle size and wind speed. Illustrative results are presented in Fig. 5, showing the particle size dependence of the reference system losses for just one test condition. At low particle sizes the measured bend transmissions were consistent with calculated gravitational and inertial deposition in a bent tube, showing a decreasing trend up to aerodynamic diameters of around 20 µm. At larger diameters the transmission functions increased again, presumably as a result of secondary transmission caused by particles bouncing or scouring after deposition. Comparing results from different

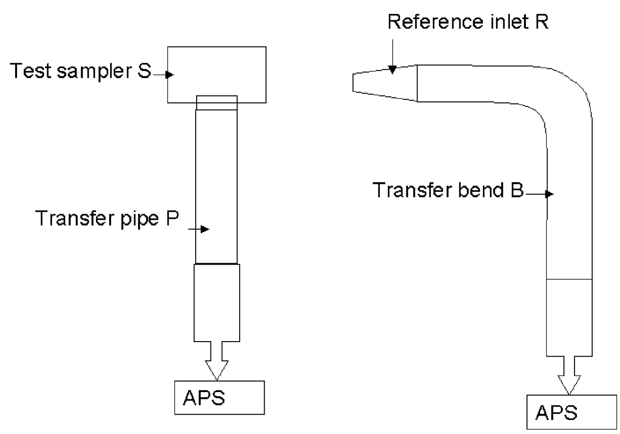


Fig. 3 Schematic diagram of connections to the Aerodynamic Particle Sizer (APS).

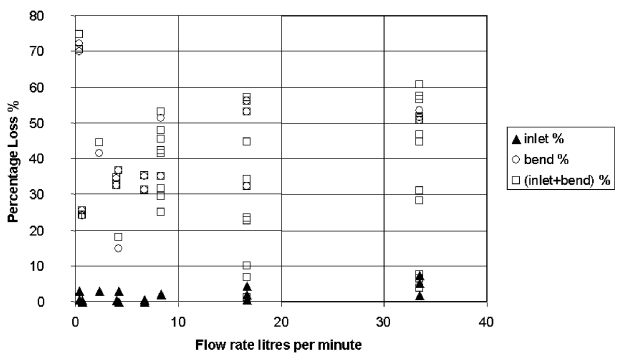


Fig. 4 Results of gravimetric loss determinations for reference inlets and bends.

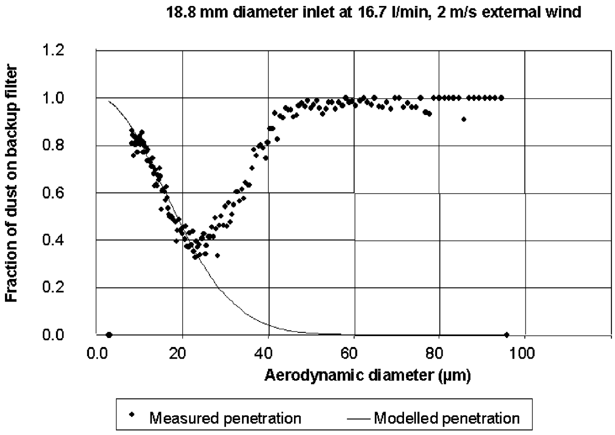


Fig. 5 Example of reference inlet + bend transmission measured using Coulter method.

Table 2 Results of Coulter™ determination of losses inside the reference isokinetic inlets

Test	Locus of minimum – efficiency axis	Locus of minimum – particle size axis	External wind/m s^{-1}	Tube flow rate/L min^{-1}	Inlet orifice/ mm
1	0.19	32	2	8.35	9.4
2	0.23	35	4	8.35	6.7
3	0.4	25	2	16.7	13.3
4	0.27	25	2	16.7	13.3
5	0.3	25	1	16.7	18.8
6	0.28	25	1	16.7	18.8
7	0.37	16	1	33.4	26.6
8	0.35	16	1	33.4	26.6
9	0.37	16	0.5	33.4	37.6

reference probes with different orifice diameters and flow rates, it was observed that the locus of the minimum transmission value (*i.e.* maximum particle loss) depended primarily on the tube flow rate, and to a lesser extent on other variables such as the orifice diameter. The minimum shifted towards larger particle diameters but lower transmission when the tube flow rate was low, and towards smaller particle diameters but higher transmission when the tube flow rate was high; see Table 2. The largest loss of particles generally occurred in the size range 20–30 µm, which given that the APS also has limited sensitivity in this range, imposes additional limitations on the sensitivity of the experimental method.

Taken together, these results show that losses within the reference system ($R + B$) are very large, and depend in a complex manner on the reference inlet geometry and flow rate. Losses within the reference inlet tip R are small in comparison to the bend losses in B. Hence if a test inlet on a straight pipe P is compared with an isokinetic reference sample taken through a bent pipe B, corrections will be needed to compensate for the differential losses in the pipes.

Losses inside the TSP and louvered inlets

The aspiration efficiency of the two inlets can only be measured if their internal losses S are negligible, so experiments were conducted to assess the magnitude of S. Tests were carried out at FHG with a monodisperse aerosol of fluorescein particles, having an aerodynamic diameter of 20 µm. Particles depositing on the inner walls of the inlets, and passing through to a filter placed at the outlet, were washed out and analysed. The proportion of wall deposit and filter deposit was assessed in relation to the total particle mass entering the sampler. At IOM, similar tests were carried out using dry aloxite particles with aerodynamic diameters of approximately 13, 26 and 46 µm. Particles depositing inside the full-scale TSP and louvered inlets were washed out and gravimetrically assessed.

Results from both sets of deposition tests are given in Table 3. For the TSP sampler, approximately 30–60% of the particles passing the inlet plane were transmitted through to the filter. For the louvered inlet, approximately 10–20% of all the particles depositing within the sampler were found on the filter. However the measured deposits included particles depositing on the plates, and these have not truly 'entered' the louvered inlet, as this begins at the narrow annular slit between the cone on the upper plate and the wall of the sampler body. For the single instance where separate determinations of deposits on the 'plates' (*i.e.* outside the inlet), 'deflector cone' and 'body' of the inlet were made, the fraction of aerosol passing through the inlet that was transmitted through to the filter (or more usually, fractionator) was approximately 30%.

The gravimetric measurements carried out at IOM included taking a reference sample of the aloxite aerosols with an isokinetic reference probe, hence giving limited confirmatory measurements of the true aspiration efficiencies of the TSP and louvered inlets, exclusive of internal losses. These data are given in Table 4.

Determination of sampling efficiency

Having established that both the TSP and louvered inlets suffer from significant internal losses within S, it was evidently not possible to measure the inlet aspiration efficiency directly using the APS/wind tunnel methodology. Instead, measurements were made of the sampling efficiency of the inlets, that is, the

Table 3 Results of gravimetric determination of losses inside the test inlets. Mass on filter is in relation to mass entering inlet

Inlet	Flow rate/ L min^{-1}	Wind speed/ m s^{-1}	Particle type	Particle size (MMAD)/µm	Percentage of mass on filter (%)	Percentage loss to:		
						Cap	Body	
TSP full scale	16.7	1	Aloxite	46	57	43	—	
TSP full scale	16.7	2	Aloxite	46	65	35	—	
TSP half scale	8.35	1	Fluorescein	20	32	68	—	
TSP double scale	33.4	0.5	Fluorescein	20	51	35	14	
						Plates	Deflector cone	Body
Louvered full scale	16.7	0.5	Aloxite	13	34	59	—	7
Louvered full scale	16.7	1	Aloxite	13	34	58	—	8
Louvered full scale	16.7	0.5	Aloxite	26	19	68	—	13
Louvered full scale	16.7	1	Aloxite	26	16	65	—	19
Louvered full scale	16.7	0.5	Aloxite	46	8	92	—	—
Louvered full scale	16.7	1	Aloxite	46	10	90	—	—
Louvered third scale	5.57		Fluorescein	20	17	35	27	21

— denotes that loss to this part is included in the column to the left.

Table 4 Aspiration efficiency data measured using aloxite aerosols and gravimetric methods

Inlet	Flow rate/ L min^{-1}	Wind speed/ m s^{-1}	Particle type	Particle size (MMAD)/μm	Replicates	Aspiration efficiency Mean	Std. dev.
TSP full scale	16.7	1	Aloxite	46	4	0.30	0.061
TSP full scale	16.7	2	Aloxite	46	3	0.42	0.051
Louvered full scale	16.7	0.5	Aloxite	13	5	1.10	0.096
Louvered full scale	16.7	1	Aloxite	13	5	1.27	0.178
Louvered full scale	16.7	0.5	Aloxite	26	5	0.98	0.167
Louvered full scale	16.7	1	Aloxite	26	5	1.43	0.123

combination of aspiration efficiency and transfer efficiency. In effect, the particle size distribution exiting from the base of the inlet is compared with the external particle size distribution, which is assumed to be measurable without bias by introducing appropriate corrections for losses inside the reference inlet system. These loss corrections were achieved in one of two ways: at HSL, the test inlet was mounted on a bend (identical to the reference inlet bend), with the top surface of the inlet oriented parallel to the side wall of the wind tunnel. Assuming that gravity plays little part in the sampling characteristics, this arrangement places the sampler inlet plane perpendicular to the oncoming wind in exactly the same way as when the inlet is placed upright without a bend. Bend losses were assumed to cancel directly using this method, since both test inlet and reference inlet systems have identical bends. The results were corroborated using an indirect method at LU and FHG, in which the transmission function of the bend, measured directly in separate experiments by comparison with a straight pipe, was used to multiply the measured efficiency data to numerically compensate for the extra losses in the reference sampling line. Note that all three laboratories were able to compare the bend loss functions applied (indirectly in the HSL case), and good agreement between the differing methods was generally obtained. The mean sampling efficiency data thus derived (at all three laboratories) were assumed to be unbiased estimates of the sampling efficiency of the inlets.

Experiments were carried out according to the plan in Table 1, in three different wind tunnels, at two different wind speeds for each inlet, and with at least two repeats of each condition carried out on two different experimental days. The data were analysed to calculate the mean and standard deviation of the sampling efficiency at particle size intervals of 1 μm, ranging from 1 μm to 20 μm aerodynamic diameter. A small number of outlying datasets were eliminated, either on the basis of experimental problems reported by the laboratories, or using procedures within Tablecurve™ software to identify outliers from the 6–9 individual datasets available for each test condition. The mean efficiency data were normalised where necessary to give sampling efficiency curves approaching unity as particle aerodynamic diameter approaches zero. Actual data points at very small diameters were lacking due to limited experimental sensitivity below 1 μm, and so normalisation was accomplished by calculating the mean measured sampling efficiency at *dae* ~1 μm (where *dae* is the particle aerodynamic diameter) and dividing the efficiency values for all other diameters by this value. Normalisation factors thus calculated were in general small, ranging from 0.95 to 1.05. The normalisation compensated for spatial variations in wind tunnel concentration, which arose with the HSL experiments (in particular) as a result of the larger spatial separation between the forward-facing reference inlets and side-facing test inlets.

Results

Sampling efficiency of the two inlets

Mean sampling efficiency data for the full-scale, double-scale and half-scale TSP inlets are shown in Fig. 6, where they are plotted as a function of measured particle aerodynamic diameter and wind speed. Gravimetric results for the full-scale TSP, obtained with 46 μm aloxite particles, indicated a sampling efficiency of 17% at 1 m s^{-1} wind, and 28% at 2 m s^{-1}.

Mean sampling efficiency data for the half-scale and third-scale louvered inlets are given in Fig. 7, where they are plotted as a function of measured particle aerodynamic diameter and wind speed. Efficiency values for the full-scale louvered inlet, obtained using gravimetric test methods at the IOM laboratory, are also shown. In all experimental results, the standard deviations of the mean sampling efficiency values at each particle size were ~0.1.

Data analysis

For inlets of simple geometry, and conditions where gravitational sedimentation is not dominant, the aspiration efficiency of an inlet is expected to depend principally on four key variables:

the Stokes number $Stk = dae^2 \gamma U/18\eta\delta$, in which *dae* is the particle aerodynamic diameter, γ is the gas density, η the gas viscosity, U the free-stream wind speed and δ the inlet orifice diameter;

the Reynolds number $Re = UD/\nu$ in which ν is the kinematic viscosity, U the free-stream wind speed and D the overall diameter of the sampler;

the wind velocity ratio $R_w = U/U_s$ in which U is the free-stream wind velocity and U_s is the sampler inlet velocity;

and the dimensional ratio $r = \delta/D$ in which δ is the inlet orifice diameter and D the overall diameter of the sampler.

Note that a slip correction term in the Stokes number is not used as our data to do extend to particle diameters below 1 μm. Q2
Our experimental scheme keeps the dimensional ratio r constant throughout, and has just two correlated values for R_w and Re, such that Re is high when R_w is high, and *vice versa*. If

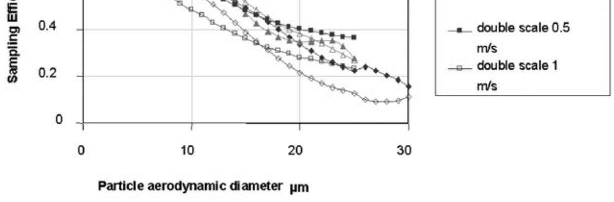


Fig. 6 Measured sampling efficiency of the TSP inlet.

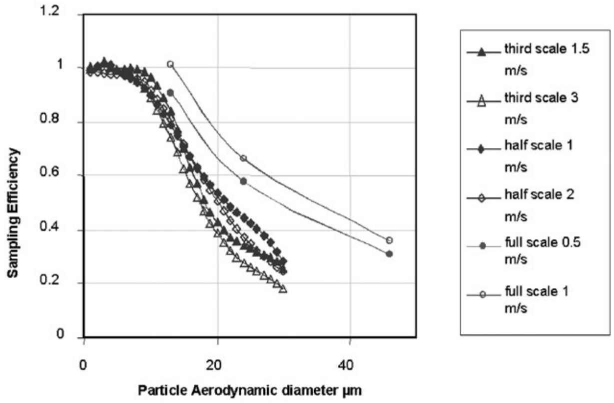


Fig. 7 Measured sampling efficiency of the louvered inlet.

the measured efficiency values are indeed dependent only on these four governing variables, we would expect the data plotted in terms of Stokes number to collapse to a single curve (for a given set of R_w, Re). Plots of efficiency data *versus* Stokes number are given in Fig. 8 and 9 for the two inlet types. [Note: these two Figures are only supplied as Electronic Supplementary Information.†]

Discussion

Methodological considerations

This experiment has shown that it is not possible to rapidly measure the aspiration efficiency of the TSP and louvered inlets in a wind tunnel, using polydisperse aerosols and time-of-flight methods. The reason for this is that both inlet types have significant internal losses. It is however possible to measure the sampling efficiency of the inlets, combining aspiration efficiency and transfer efficiency. This provides useful data as it quantifies the fraction of PM that is available for collection (or further fractionation) downstream of the inlet.

A major challenge in utilising time-of-flight methods in a wind tunnel is to obtain unbiased samples of the reference concentration. The geometry of the test system means that a pipe with a bend must be used to connect isokinetic inlets to the particle analyser. Losses in this reference inlet system are large, being dominated by deposition in the bent pipe rather than the isokinetic reference inlet itself. In practice, with a solid spherical glass aerosol, transmission losses through the inlet + bend are smaller than those predicted theoretically, because of secondary transmission effects at higher particle sizes. The requirement to make corrections for bend losses adds extra uncertainty to the experiment, and the size-selective nature of particle losses degrades the usable range of the experimental data. Lessons learnt from this work would enable losses to be reduced in future, by optimising the design of the reference probes and tubes so as to maximise particle transmission in the required size range.

Interlaboratory errors in the wind tunnel determination of sampler performance have rarely been subject to rigorous study. In this work, repeat tests both within and between testing laboratories showed standard deviations in measured efficiency values in the region of 10%, indicating that results in different laboratories were generally as consistent as repeated results in a single laboratory. Methodological comparison is possible with earlier tests of PM10 inlets conducted in wind tunnels, but using monodisperse fluorescently-tagged aerosols followed by chemical analysis, rather than time-of-flight methods. An analysis of inter-laboratory test results obtained for PM inlets tested in different wind tunnels is presented by Kenny and Bartley.[8] In the reported experiments, inter-laboratory standard deviations in efficiency values were found to be in the region of 6%. Intra-laboratory variations were smaller than inter-laboratory variations. This level of reproducibility represents performance attainable using very carefully standardised testing protocols, with close attention to experimental error in each laboratory. In contrast to our work, the experimental method used was time consuming, requiring at least two orders of magnitude more time to carry out than our time-of-flight method. With closer attention to standardising methodology, we expect that the experimental errors for time-of-flight test methods can be further reduced.

One limitation of our experiments is the fact that data are confined to low wind speeds, whereas for sampling in the ambient environment, performance data up to 7 m s^{-1} are required. The methods we have developed can be applied in larger wind tunnels able to achieve suitably high wind speeds. Our experimental design was limited to lower wind speeds in order to allow us to test the small-scale inlets under aerodynamically similar conditions to their full-scale counterparts, which requires the wind speeds to be scaled accordingly. This requirement does, therefore, limit the applicability of the data. Likewise, in order to test the scaling hypothesis the insect screens of the louvered inlet were not used, and these are known to have some effect on performance.

Assessment of sampling efficiency data

For both inlets, Figs. 8 and 9 (supplied as ESI† only) indicate that sampling efficiency is not dependent solely on the dimensionless aerodynamic numbers *Stk*, *Re* and R_w, since the data from different inlet scales do not coincide. Although these variables will govern aspiration, we have observed that only around 30–50% of the aspirated aerosol is transmitted through the inlets. Aerodynamic mechanisms may account for primary losses of particles to the internal walls of the inlets, however secondary transmission effects are also important for solid particles. These depend on the surface and material properties of both the particles and the inner walls. In such complex sampling systems it is not surprising that quantitative models to describe the inlets' size-selective sampling characteristics are elusive.

Qualitative trends in performance of the TSP inlet can be observed in Fig. 6, from which one can see that particle size range up to *dae* $\sim$30 µm, (a) increasing the wind speed for a given inlet scale tends to decrease the sampling efficiency, and (b) increasing the inlet scale for a given wind speed also tends to decrease the sampling efficiency. Limited data at much larger particle sizes (reported in Results) do not follow this trend, however may well be affected by particle bounce effects. Overall, the results for the TSP suggest that its *aspiration efficiency* is less than one (as confirmed at one particle size in Table 4), and aspiration decreases as external wind increases. The TSP inlet has low sampling efficiency for larger particles in the PM10 range, and given that it is not used with any downstream particle fractionator, is likely to give biased PM concentrations that vary with external winds when large particles are present.

In the case of the louvered inlet, the data in Fig. 7 indicate that (a) increasing the wind speed for a given inlet scale tends to slightly increase the sampling efficiency, at least for the full-scale inlet; and (b) increasing the sampler scale for a given wind speed tends to increase the sampling efficiency. These trends are consistent with the hypothesis that the aspiration efficiency of the louvered inlet is greater than one at the wind speeds tested (*i.e.* conditions where $U > U_s$), and it increases as wind speed increases. Actual measurements of aspiration efficiency at two particle sizes, in Table 4, confirm that it is greater than 1 in moving winds. This interpretation is further supported by data obtained in calm air, for example as published by Lai and Chen,[5] which were verified by (unpublished) test results obtained in calm air at HSL for R&P Inc. The calm air sampling efficiency is lower that the moving air efficiency, having 50% efficiency at around 15 μm.

Supporting evidence that the full-scale louvered inlet has high sampling efficiency across the full PM10 particle size range, and up to high wind speeds, is demonstrated by its consistent performance in a wide range of conditions when combined with a PM10 fractionator.[6] Our results suggest that scaling down the inlet to operate at lower flow rates reduces its sampling efficiency, but not to the extent that it would compromise its use for monitoring PM10 in moving winds. The PM10 performance in very low wind conditions where $U < U_s$, for example indoors, would need to be verified for the small scale inlets. Small-scale sampling for downstream PM2.5 fractionation is less likely to be subject to inlet bias in very low wind conditions, and is definitely feasible above 1 m sec^{-1} as demonstrated by Fig. 7.

Conclusions

Systems have been developed for rapid testing of PM inlets in moving air, using a time-of-flight technique. Using this methodology, particle losses in the connections to the APS analyser were found to be much more important than anticipated. As a result it was only possible to measure the sampling efficiency of the inlets, not the aspiration efficiency.

The sampling efficiencies of two types of PM inlets were tested, using both full-scale and scaled versions of the inlets. The efficiency data could not be readily modelled using dimensionless aerodynamic parameters, probably as a result of the complex mechanisms governing losses within the inlets, particularly for solid aerosol particles. For these inlets therefore, it is not possible to quantitatively predict the impact of scaling up or down to operate at different flow rates by using simple aerodynamic 'rules'; experimental validation of performance would be required. Rapid wind tunnel testing of performance was shown to produce results with acceptable reproducibility and repeatability, but subject to systematic bias unless effective means were employed to eliminate reference system losses.

Our experimental data yielded useful qualitative data on the potential to develop new inlets from existing designs, able to operate at either higher or lower flow rates. The low-volume louvered inlet was found to have sampling efficiency that is relatively insensitive to external winds, increasing very slightly as the external wind increases. Under all conditions expected in practical use the inlet aspirates sufficient PM to allow either PM10 or PM2.5 to be selected downstream. The inlet can be scaled down to operate at lower flow rates without negatively impacting on performance, except possibly in exceptionally low wind conditions for PM10. Because the louvered inlet is always used in combination with a fractionator, it is acceptable for it to over-sample particles through operating at sub-isokinetic inlet conditions; the excess particles are removed downstream of the inlet by the fractionator.

The TSP inlet displays more marked external wind speed dependence and is likely to under-sample the coarse end of the PM10 fraction at moderate and high external winds. As this inlet is generally not used with a downstream size fractionator, utilising it in different wind conditions, or scaling to operate at different flow rates, will bias the measured aerosol concentration.

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Aspiration and sampling efficiencies of the TSP and louvered particulate matter inlets

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This paper presents sampling efficiency data for two PM inlets, and discusses whether the inlets can be scaled in order to develop pollution monitoring instruments operating at different flowrates, without compromising performance.

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