Numerical Simulations of the Sampling Performance of a Large Particle Inlet

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ABSTRACT

The sampling performance characteristics of a funnel-shaped large particle inlet (LPI) were obtained experimentally using wind-tunnel measurements and the results compared against computational fluid dynamics (CFD) predictions. In the wind-tunnel, a moving injector system was used to inject polydisperse particles uniformly over the tunnel cross-section and a pair of Aerodynamic Particle Sizers were used to measure size-resolved sampling efficiencies of the inlet at 3 m s^{-1} . The wind-tunnel results differed from earlier published CFD predictions, necessitating a numerical re-analysis of the inlet performance with a higher order turbulence model and a finer mesh grid appropriate for accurate particle turbulent dispersion modeling. The new simulations revealed non-uniformity in the spatial distribution of particles exiting the inlet. As particle measurements were only made from a sub-set of the inlet flow, the spatial distribution of particles needed to be considered for an accurate comparison with numerical simulations. Accounting for the spatial non-uniformity of particles exiting the inlet resulted in reasonably good comparison of simulations with experimental data. The simulation results suggest that the current LPI design results in an almost wind-speed independent sampling performance for particles smaller than $10 \text{ }\mu\text{m}$ and a cut-size of $\sim 20 \text{ }\mu\text{m}$ for wind-speeds as large as 4.5 m s^{-1} . The CFD results suggest that a simple redesign will result in effective sampling of larger particles but will increase the wind-speed dependence of the inlet's sampling efficiency. Further wind-tunnel testing is required to validate the predicted sampling efficiencies at larger sizes and higher wind-speeds.

Keywords: LPI, inlet, sampling efficiency, PM_{10} , large particles, wind-tunnel

INTRODUCTION

Monitoring of airborne particles has typically been driven by human health concerns associated with particle inhalation. Inhalable particulate matter can be as large as 100 μm in aerodynamic diameter, but the primary particles of health concern are smaller than 10 μm (i.e., PM_{10} ; Brunekreef and Forsberg, 2005, Pope and Dockery, 2006). Particles larger than 10 μm ($\text{PM}_{>10}$) have been of interest from an environmental perspective, because these particles can contribute significantly to the total aerosol mass and may dominate the deposited fraction. The large surface area of $\text{PM}_{>10}$ particles aids diffusional-scavenging of carcinogenic material (such as polycyclic aromatic hydrocarbon) and other pollutants (like nitrogen oxides) and because of their significant deposition rates, $\text{PM}_{>10}$ particles can be a significant source of such pollutants to the Earth's surface.

A common source of dry $\text{PM}_{>10}$ is fugitive dust (FD) which is generated by the mechanical disturbance of soils, such as wind, vehicular movement on unpaved roads, construction operations and agriculture activities. The size distribution and composition of the $\text{PM}_{>10}$ particles will, thus, vary with ambient and source conditions, and must be established from local measurements. The significant inertia of $\text{PM}_{>10}$ particles complicates representative sampling of these particles under varying wind conditions. Using a large diameter (0.6 m) vertical sample tube, Lundgren and Paulus (1975), were able to successfully sample particles in the size range of 0.3 to 100 μm in wind speeds up to 11 km/hr. Their measurements showed that particles in the size range of 5 -100 μm constituted a separate mass distribution mode and that these particles dominated the total airborne aerosol mass. In calculating large particles size distributions, however, the exact sampling characteristics of their inlet were not considered.

Using wind-tunnel measurements, Wedding et al. (1977) and McFarland et al. (1980) evaluated sampling efficiencies of different large particle inlet designs. The wind-tunnel test results showed that large particle inlets had sampling efficiencies that were dependent on particle size, wind-speed, and the design of the inlet. A commercial hi-volume sampler designed for sampling total suspended particulates (TSP) was seen to have strong wind-speed dependent sampling efficiency for particles larger than $\sim 8 \mu\text{m}$, with 50% sampling efficiency $\sim 20 \mu\text{m}$ at a wind-speed of 24 km/hr. McFarland et al. (1980) tested the hi-volume sampler in combination with a size-selective inlet and showed that the combination of the two resulted in a wind-speed independent sampler performance, with a cut-size of 15 μm .

Recently, two independent efforts to design and test compact inlets for sampling large particles using computational fluid dynamics (CFD) were introduced. Using CFD simulations, Tang et al. (2010) calculated sampling efficiencies of a moderate flow (100 LPM) omni-directional inlet developed for sampling particles in the size range of 2-20 μm . The bell-shaped inlet was seen to have wind-speed dependent sampling efficiencies, with particles smaller than 20 μm sampled at wind-speeds as high as 7 m s^{-1} . The simulation results were seen to closely match experimental data, providing confidence in using CFD simulations for design and evaluation of large particle inlets, particularly under moderate flow conditions.

Lee et al. (2008) used CFD simulations to design a hi-volume (~ 1000 LPM) omni-directional inlet for sampling particles as large as 100 μm over a wind-speed range of 1-7 m s^{-1} . While Tang et al (2010) showed the validity of CFD predictions for inlet evaluation, the high flow regime of this inlet necessitates independent evaluation under controlled conditions. As part of this study, wind-tunnel experiments were conducted to determine the sampling efficiencies of Lee et al. (2008)'s large particle inlet (LPI). The details of the wind-tunnel experiments and additional numerical simulations are presented here.

MATERIALS AND METHODS

The LPI design of Lee et al. (2008) is shown in Figure 1. Lee et al., (2008) used a series of parametric CFD simulations to optimize the inlet dimensions to ensure effective sampling of particles as large as 100 μm at wind speeds ranging from 1-7 m s^{-1} . With a narrow slit width (indicated as h_s in Figure 1) and a flowrate larger than 700 LPM, the flow was predicted to enter the inlet nearly axi-symmetrically from the ambient. The axi-symmetric nature of the flow field was shown to be critical in turning particles from the horizontal to the vertical direction. The inlet geometry did not include any screen or housing to keep out insects or large precipitation drops/particles.

Figure 1 here

To validate the CFD-calculated sampling characteristics of the LPI, controlled wind-tunnel experiments were performed in an aerosol wind tunnel at Clarkson University (<http://www.clarkson.edu/windtunnel/>). The wind-tunnel has a test section of dimensions: 1.22 m width, 0.91 m height, and 6.09 m length. At the entrance to the wind-tunnel, a bank of 62 HEPA filters was used to filter out particles from the air entering the tunnel. The air was then passed through a flow-settling section consisting of a honey-comb structure and a series of screens to ensure laminar and uniform flow over the entire wind-tunnel cross-section. The velocity uniformity in the test section is within 5% at a wind speed of 3m/s. The turbulence intensity is $\sim 5\%$. The exhaust air from the tunnel was then discharged through a removable duct outside the building.

For inlet performance testing, a uniform concentration of test particles was required over the cross-section of the wind-tunnel. With a stable, uniform concentration in the wind-tunnel, a single point measurement of freestream concentration would be sufficient to determine the upstream aerosol characteristics. Uniform particle concentration in the wind tunnel can be achieved using multiple identical particle injectors spread over the tunnel cross-section (Heist et al. 2003). Such an injection approach would, however, result in significant blockage of the cross-section, and influence the wind-tunnel flow characteristics. As an alternative, particles could be introduced via a single injector system coupled with a turbulence-generating mesh grid or a fan to spatially spread the particles (McFarland et al. 1984; Witschger et al. 1997; Lee et al. 2013). This approach allows for near uniform spatial distribution of particles in moderately sized wind-tunnels, but results in significant turbulence over the entire wind-tunnel flow. To ensure uniform particle concentrations over a wind-tunnel with large cross-sectional area, a different approach is required.

In the current study, a single downward-facing vertical injector was coupled with a XY-translator and a small turbulent screen just upstream of the injector. Stepper motors were used to operate the XY-translator and the speed of its movement and start/end points were controlled by a LabView program. The particles were introduced in the wind-tunnel upstream of the test section by moving the injector in a pre-determined path, as shown in Figure 2. The entire motion takes approximately 30 minutes to complete. This simulated the effect of multiple injectors in the tunnel, without creating the same extent of tunnel blockage. Arizona road dust (A4 coarse; Powder Technology Inc. MN) particles were aerosolized using a dry powder disperser (SAG-410 TOPAS GmbH). The particles were introduced into the wind-tunnel through a flexible conductive tubing that was connected to the XY-translation system located on top of the wind tunnel test section. A pneumatic vibrator was attached to the particle injection tube to ensure that there was no particle build up in the delivery tube. A 15 cm $\times$ 10 cm mesh screen was located at the end

of injection tube to generate local turbulence and help spread particles downstream of the injection location.

Figure 2 here

To determine the consistency of the dust generation over time, real-time particle size distributions were measured using the Aerodynamic Particle Sizer (APS; TSI 3321) placed in the wind tunnel with the sampling tube facing upstream into the flow seeded by the dust feeder without movement of the injection system. The size distributions of the generated particles were such that approximately $80 \text{ particles cm}^{-3}$ were generated at the smallest particle sizes of interest ($2 \text{ }\mu\text{m}$) and concentrations monotonically decreased to $\sim 0.5 \text{ particles cm}^{-3}$ for the largest particles measured by the APS ($20 \text{ }\mu\text{m}$). The total concentrations were seen to vary less than $\pm 10\%$ over a 30-minute measurement time period.

To ensure that the particle seeding in the tunnel spanned the entire sampling volume of the LPI, the dust feeder outlet was moved vertically and horizontally about the centerline of the inlet until the injected particles were outside the sample flow region of the LPI. The width of the sampling volume was $\sim 16 \text{ cm}$ at a wind speed of 3 m s^{-1} . The sampling region width was considerably smaller and less dependent on wind speed than the range of sampling heights.

The particle concentrations in the wind-tunnel were measured using an APS at 12 different locations (4 in the horizontal and 3 in the vertical direction) in the test section over an area of $0.38 \text{ m} \times 0.1 \text{ m}$. The APS was placed on its side, so as to orient the instrument's sample port to face the wind-tunnel flow. Placing the APS in the tunnel resulted in $\sim 10\%$ blockage of the wind tunnel. In Figure 3, the particle concentrations corresponding to the inlet sample flow region ($0.2 \text{ m} \times 0.03 \text{ m}$) relative to that over the entire measurement region are shown as a function of particle size for a freestream velocity of 3 m s^{-1} in the wind tunnel. A maximum non-uniformity of $\pm 20\%$ over the wind-tunnel cross-sectional area of interest was observed.

Figure 3 here

The wind-tunnel tests were conducted at a wind speed of 3 m s^{-1} ($\sim 10.8 \text{ km hr}^{-1}$). The blockage of wind-tunnel cross section was $\sim 10\%$ and the cross-sectional uniformity of the particle concentration was, $\pm 20\%$. Note that our measured variance was over a region greater than the sampling area and it is expected that the variance within the central area of this region would be smaller. Also, some of this variance is a result of the temporal variability of our injection system.

LPI Characterization

Wind-tunnel characterization of the LPI performance required measurements of particle size distributions upstream and downstream of the inlet, ideally made simultaneously with two identical detectors. In the current study, two APSs were used for simultaneous measurement of upstream and downstream size distributions over a diameter range of $0.5\text{-}20 \text{ }\mu\text{m}$. Before wind tunnel experiments, a side-by-side 20-minute comparison was run to obtain the relative counting efficiency of the two APSs. The mean number concentrations for each minute and bin size were compared. For particle diameters >2 and $<10 \text{ }\mu\text{m}$, the ratio varied between 0.9 and 1.2. For larger particles which are not measured as efficiently by the APS the variation of the ratio was slightly larger. To ensure that the APS freestream measurements were made unobtrusively in the vicinity of the LPI, the APS was located downstream of the inlet and sampled from flow adjacent to the LPI using a long copper tube ($0.2 \text{ m long} \times 2 \text{ cm ID}$). The

inlet of upstream sample tube was located $\sim 0.2\text{m} \times 0.2\text{m}$ away from the center of LPI. The downstream APS sampled from the LPI exit flow, with a 1 cm ID thin wall sample tube extended into a 5 cm ID PVC elbow attached to the exit of the LPI. The wind-tunnel test setup is illustrated in Figure 4.

Figure 4 here

The flow velocities in the upstream and downstream APS sample tubes differed from the corresponding freestream values, resulting in size-dependent anisokinetic enhancement of particles into the APS sample tube. The sample tube anisokinetic enhancements were accounted for using the empirical equation of Belyaev and Levin (1974). The size distributions measured by both the upstream and downstream APS instruments were also corrected for gravitational sedimentation loss (Thomas, 1958; Fuchs, 1964) and inertial turbulent deposition (Lee and Gieseke, 1994). Details of these corrections are included in the Appendix. The sampling efficiencies of the LPI were obtained from the ratio of the corrected size distributions obtained from the two APSs, after accounting for the relative counting efficiencies of the two units. In calculating the LPI sampling efficiency, the only size bins considered were those with more than $0.001 \text{ particles cm}^{-3}$ (corresponding to 1 particle per minute) in the upstream APS. A sample calculation of LPI efficiency is attached in Appendix.

Figure 5 here

The sampling efficiencies obtained from the wind-tunnel studies are shown in Figure 5. The sampling efficiencies were seen to be ~ 1 for particles smaller than $\sim 4 \mu\text{m}$, decreasing for larger particles. For particles larger than $10 \mu\text{m}$, particle number counts measured by the two APS units were low, resulting in significant uncertainty in the calculated efficiencies. A comparison of the experimental data with the CFD simulation results of Lee et al. (2008) are shown in Figure 5. For particles smaller than $4 \mu\text{m}$ diameter, the experimental results reasonably matched previous numerical results. For larger particle sizes, the calculated sampling efficiencies were higher than those observed. Also, a non-monotonic trend in the data was observed for particles in the size range of 4 to $10 \mu\text{m}$. This trend could be because of the combination of small errors in the different correction factors used (relative detection efficiencies of the two APS units, gravitational loss, anisokinetic sampling efficiency, and turbulent deposition loss) that might have become significant in this size range.

To understand the reasons for the discrepancy in the overall trend of experimental data and the model predictions, the original simulation results of Lee et al. (2008) were revisited, with particular focus on improving the treatment of turbulent dispersion on particle trajectories. Lee et al. (2008) used an isotropic turbulence model that is not entirely appropriate for the LPI flows and the mesh density was not refined near the walls. With improved availability of computational resources, a numerical re-analysis of the LPI performance was conducted considering a high-accuracy turbulence model and refined mesh grids in boundary layer.

RE-ANALYSIS OF LARGE PARTICLE INLET

The Reynolds number for flow in the LPI is defined as $\text{Re} = \frac{4Q_{LPI}}{\nu\pi d_{out}}$, where Q_{LPI} is the total sample flow rate of LPI, ν is kinetic viscosity of air and d_{out} is the ID of vertical tube. For the large sample flow

rate required for effective LPI operation, the Reynolds number for flow in the instrument is large ($>10^4$). Accurate prediction of particle trajectories under these conditions requires a fine mesh near the walls of the LPI, with a y^+ value ~ 1 for the wall-adjacent cells (Tian and Ahmadi, 2007), which was not satisfied in Lee et al. (2008). With this high mesh resolution in the near wall regions, the laminar sub-layer and the velocity fluctuation of turbulence in the normal direction to the wall would be predicted more accurately, allowing for improved predictions of particle loss to the inlet walls. In addition to a fine mesh, the choice of the turbulence model is critically important. Past studies have shown that particle trajectory calculations with the standard k- ϵ model or standard wall function model (as used in Lee et al., 2008) results in over-prediction of particle deposition rates (or wall loss) for most particle sizes in a channel flow (Tian and Ahmadi, 2007). The combination of a higher order turbulence model, such as Reynolds Stress transport (RSM) model, and a refined mesh are computationally expensive, but critical for accurate particle trajectory calculation for conditions such as those encountered in the LPI. Another limitation of the inlet efficiencies calculated by Lee et al. (2008) was that they were based on average particle concentrations exiting the LPI. The efficiencies calculated in this manner would be appropriate for filter measurements at the exit of the LPI. However, with real-time instruments used at the LPI exit, such as in the current experimental study, only a sub-set of the LPI flow was analyzed and under such circumstances, the knowledge of the spatial distribution of particles at the LPI exit becomes important.

Numerical Modeling

A re-analysis of the LPI sampling performance was conducted using ANSYS FLUENT 14.0 software, with a finer mesh size (~ 10 million cells generated using ANSYS Meshing) and a larger external domain than used previously by Lee et al. (2008). To accurately predict particle loss under turbulent dispersion conditions, the near-wall regions were refined by adding five prism (boundary) layers.

The flow field was modeled as steady with Reynolds Stress Transport turbulence model (RSM) and enhanced wall function. The boundary conditions were set as velocity inlet and outlet-vent for the wind tunnel that housed the inlet. The turbulent intensity was set to 5%, consistent with the conditions of Lee et al. (2008). Particles of unit density (1 g cm^{-3}) were injected uniformly from a plane 0.5m upstream of the LPI. Particle trajectories were calculated considering turbulent dispersion, using the discrete random walk model with a random eddy lifetime (timescale constant was set as default 0.15). As the particle Reynolds numbers could be significantly higher than 1 in regions of large velocity gradients, the ultra-Stokesian drag formulation was used for particle trajectory calculations. All wall boundaries were set to trap particles coming in contact with them. The different parameters used in this study are listed in Table 1 and compared against those used by Lee et al. (2008).

Table 1 here

CFD SIMULATION RESULTS

Analysis of Flow and Particle Trajectories

Upstream uniformity of particles

The structure of internal flow field critically influences the distribution of particle positions at the exit of the LPI. The typical flow field within the LPI is shown in Figure 6. At low wind speeds (1 ms^{-1})

and high sample flow rates (1760 LPM), the LPI sample flow is seen to enter nearly omni-directionally. Increasing the wind-speed (3 ms^{-1}) and at a lower LPI sample flowrate (850 LPM), the pathlines of the sampled flow within the LPI were seen to be non-symmetrical, i.e. the flow entered primarily from the direction of the wind.

Figure 6 here

The asymmetry in the flow entering the LPI affects the nature of the flow field exiting the inlet. The flow characteristics in the LPI vertical tube are shown in Figure 7. As the flow was turned from the horizontal to the vertical direction, a recirculatory secondary flow was established in the vertical tube; the characteristics of which varied over the length of the vertical tube. The secondary flow started at the entrance of the vertical tube and as the flow moves towards the exit, the recirculation regions are diminished significantly. The nature and magnitude of the secondary feature inside the LPI will critically determine particle loss within the inlet and the spatial distribution of particles at the exit of the LPI.

Figure 7 here

Spatial distribution of particles downstream of LPI

From particle trajectory calculations, the size-dependent particle spatial distribution at the exit of the inlet was recorded and is shown for two particle sizes in Figure 8. Particles of $3 \mu\text{m}$ diameter were seen to be nearly uniformly distributed over the exit region. On closer observation, however, it can be seen that these particles were highly concentrated along the edge of the exit region. This is a result of the interaction of the secondary recirculation flow with particles in this size range. Larger particles ($50 \mu\text{m}$) are, however, clearly seen to be non-uniformly distributed at the LPI exit, with higher concentration in the central region along the wind direction. This spatial non-uniformity is because of the interaction of the incoming particles with the vertical walls as they navigate the curvature of the LPI.

Figure 8 here

This non-uniformity in particle distribution at the inlet exit critically influences downstream measurements made from selective detection of particles over a small location at the sample exit. The extent of particle spatial non-uniformity was characterized as a ratio of particle concentrations in the central (10 mm diameter) region of the LPI exit flow, consistent with the region where a probe for an instrument such as the APS might sample from, to the average particle concentration over the entire exit flow. This ratio, referred to here as the concentration ratio, was determined from CFD simulations and the averaged results for wind speed of 1 ms^{-1} to 4.5 ms^{-1} are shown in Figure 9. The concentration ratios at each wind speed were obtained by averaging particle concentrations at 5 locations – the center of the LPI exit and 4 locations around the center, 3 mm away. This ensured that the calculated concentration ratios were not very sensitive to the particle statistics at any one location. The concentration ratio was seen to increase with particle size, suggesting that larger particles were increasingly concentrated in the central region of the exit flow. With a flowrate of 1760 LPM, the concentration ratio for particles smaller than $\sim 10 \mu\text{m}$ was ~ 1 , higher than that obtained with a sample flow of 850 LPM. This reflects the reduced contribution of the secondary flow in moving the 1-10 μm sized particles to the vertical tube edge at higher sample flows. The non-monotonic nature of the ratio at larger particle sizes reflects the complex interaction of particles with the LPI flows and geometry. This concentration ratio must be considered in comparing CFD calculated sampling efficiencies with any experimental data obtained from a sub-sample

probe in the LPI exit flow, as done in the current study.

Figure 9 here

The relation between concentration ratio and LPI geometry was studied by varying the LPI slit opening (h_s) and exit diameter (d_{out}). For a selected d_{out} (4cm), the averaged concentration ratio for different h_s (5mm, 2cm and 3cm) is shown in Figure 10. A common trend of increasing concentration ratio with particle size was observed for all cases. The extent of non-uniformity in the particle spatial distribution in the LPI exit flow was largely independent of slit width. The effect of varying the exit diameter (d_{out} = 8cm, 4cm) on the LPI performance is also shown in Figure 10. With a larger exit flow area, a relatively size-independent concentration ratio of 0.7 to 0.9 was observed for all particle sizes < ~20 μ m. This improvement in the uniformity of the spatial distribution is because the larger tube diameter results in greater residence time of particles in the vertical tube, allowing for turbulence to uniformly disperse particles over the cross-section of the tube. For the largest particle sizes (> 20 μ m), however, the turbulent eddies are not sufficiently strong to disperse the particles, resulting in high concentrations of these particles in the central region.

Figure 10 here

LPI Efficiency

The particle spatial non-uniformity in the flow exiting the LPI results in sampling efficiencies calculated from the average particle concentration to be very different from that calculated based on a central subset of the exit flow. For comparison with experiments, the sampling efficiency must be appropriately calculated from the central subset of the exit flow, as in the experiments. For 3D simulations, the central flow sampling efficiency was calculated as:

$$\text{Efficiency} = \frac{N_{\text{sample}}}{Q (N_{\text{up}} / (V_{\infty} A_{\text{inj}}))} \quad (1)$$

Where Q is the APS flow rate (5 LPM), N_{sample} is the number of particles in the center of exit flow, corresponding to the area of the APS sample probe (inner diameter: 10mm), and N_{up} is the number of particles injected well upstream of the inlet, where the flow velocity is V_{∞} , over an area of A_{inj} . The particle loss in the LPI was calculated similarly, with N_{sample} representing the number of particles lost to the internal walls of the LPI and Q representing the total sample flow through the LPI.

The CFD-calculated sampling efficiencies considering the central flow region (5 LPM) was compared against wind-tunnel experimental results obtained with an APS sub-sampling from the LPI in Figure 11. The sampling efficiencies calculated using different turbulence models and mesh densities (listed in Table 1) are shown for a wind speed of 3 ms^{-1} . Independent of the turbulence model used (k- ϵ or RSM model), ignoring turbulent dispersion resulted in significant under-prediction of particle wall loss and over-prediction of sampling efficiency for almost all sizes. With particle turbulent dispersion calculated using the k- ϵ model, however, wall loss was significantly over-estimated. Sampling efficiencies obtained with a combination of RSM turbulence model, particle turbulent dispersion, and a fine mesh ($y^+ \sim 1$) was seen to result in the best prediction of the experimentally observed LPI efficiency.

Figure 11 here

LPI Sampling Characteristics

Using the validated modeling approach (fine mesh, RSM, turbulent particle dispersion), the LPI sampling efficiencies can be characterized as a function of operating conditions. In this study, the LPI sampling performance was calculated as a function of ambient wind-speed, sample flowrate, and LPI geometry.

Sample Flowrate

Lee et al. (2008) showed that a high sample flowrate ($> \sim 750$ LPM) is required to maximize the area of the sample flow entering the LPI, with near axisymmetric aspiration under moderate ambient wind speeds. To determine if the sampler performance was strongly dependent on the sample flowrate, new simulations were conducted for two flowrate cases of 850 and 1760 LPM, consistent with flows achievable with a commercial hi-vol blower (BBA14-122HEB, Northland Motor BLDC blower, TN). The sampling efficiencies calculated for both these flowrates were seen to be similar. This was because, at higher flowrates, the more axi-symmetric entrance of the flow into the inlet from the ambient aids the turning of particles from the horizontal to the vertical direction while the higher particle velocities, and hence their Stokes numbers, make it more difficult to turn the particles. The combination of these opposing effects results in the similar sampling efficiencies at the two flowrates studied. Simulations conducted with varying freestream turbulence intensities (5% and 10%) suggested that the sampling efficiencies were largely invariant (less than 5% change) for the two turbulence intensity cases.

LPI Geometry

To determine the sensitivity of the LPI performance to its geometry parameters, CFD simulations were conducted with varying inlet width (h_s) and outlet diameters (d_{out}). Lee et al., (2008) recommended that a LPI design with an h_s value of 1 cm and a d_{out} of 4 cm had the best sampling performance based on average efficiency over the exit area. The current results, consistent with the observations of Lee et al. (2008), suggest that a larger h_s value (2 cm) results in a sampling efficiency that is higher for most particle sizes at a given sample flow rate, but also more dependent on wind-speed than for the case of smaller h_s . Thus, when sampling particles larger than $40 \mu\text{m}$ is desired, a larger h_s is recommended; otherwise the choice of h_s value of 1cm is probably the most appropriate. For the two outlet diameters (4cm and 8cm) studied, the calculated LPI sampling efficiencies are seen to be very similar. Thus, the exact choice of the downstream outlet size is not critical with respect to overall efficiency measurements.

Ambient Wind Speed

The sampling efficiencies of a LPI with configuration of h_s of 1cm, d_{out} of 4cm, and a sample flowrate of 1760 LPM were determined for ambient wind-speeds in the range of $1 - 4.5 \text{ ms}^{-1}$. The LPI sampling efficiencies were calculated using the two approaches discussed above— average concentrations over entire exit flow and from a central sub-sample region of 5 LPM flowrate — and are shown in Figure 12. Also shown in Figure 12 are the size-dependent particle wall loss factors. The wind-speed dependence is indicated as error bars, with the magnitude of the error bars representing the range of efficiency values over the wind speeds studied. The sampling efficiency based on the entire exit flow, suggests that particles smaller than $3 \mu\text{m}$ can be collected from the LPI largely independent of wind speed, while the collection of particles in the size range of $3 - 10 \mu\text{m}$ will have moderate wind dependence. For larger particles, the sampling efficiency was seen to show significant wind-speed dependence. At low wind

speeds (e.g., 1 ms^{-1}), the near symmetric nature of the flow field aids sampling of large particles in two ways: 1) with the sample flow entering from almost the entire entrance area, the flow velocity is low, resulting in low inertia of particles in the region where the flow needs to be turned to the vertical tube; 2) with a symmetric entrance of sample flow, the counter flow influence is most effective, acting to slow particles and help turn them into the vertical tube. At higher wind speeds, the sample flow largely enters from one direction, and thus the sample flow velocity in the LPI is high and the counter flow effect is largely absent. In combination with a downstream multi-stage large particle impactor or an optical sizer, accurate large particle size distribution measurements are possible with the LPI. When the LPI is operated with downstream instruments that only detect particles from a sub-sample of the exit flow (e.g., APS or a low-flow optical particle counter) the relevant LPI sampling efficiency should account for the concentration ratio (Figure 10). This sub-sample based sampling efficiency is also shown in Figure 12. The sub-sample based sampling efficiency was seen to be relatively size- and wind-speed-independent for particles smaller than $10 \text{ }\mu\text{m}$, suggesting its applicability as an accurate inlet for real-time PM_{10} monitoring instruments.

Figure 12 here

From the new simulations it was concluded that a LPI designed with an h_s of 1cm and d_{out} of 4cm will have an almost size-independent sampling efficiency $> \sim 80\text{-}85\%$ for particle sizes smaller than $10\mu\text{m}$ and a sampling efficiency cut-size of $\sim 20 \text{ }\mu\text{m}$. The validated CFD simulations suggest that particle wall losses will increase with particle size, with maximal loss ($\sim 25\text{-}40\%$) associated with particles of diameters $\sim 30 \text{ }\mu\text{m}$, especially at higher wind speeds. For increased sampling efficiency of particles larger than $20 \text{ }\mu\text{m}$, a bigger slit width ($h_s = 2\text{cm}$) will be required.

CONCLUSIONS

Ambient sampling of particles larger than $10 \text{ }\mu\text{m}$ is complicated by the significant inertia of these particles. A CFD-based design of a large particle inlet (LPI) was introduced by Lee et al. (2008). In this study, wind-tunnel experiments were conducted to test the CFD predictions of LPI sampling performance. The particles were introduced into the wind-tunnel using a newly designed moving injection system. The data from wind-tunnel studies were seen to differ from the CFD results of Lee et al. (2008), necessitating a CFD re-analysis of the inlet. Using a higher order turbulence model (RSM) and a finer grid that satisfied the mesh quality requirement for accurate particle trajectory calculations ($y^+ \sim 1$), new CFD results were obtained and were seen to match reasonably well with the wind-tunnel data. The validated CFD calculation approach was then extended to re-examine the dependence of the LPI sampling efficiency on the flowrate, wind conditions, and the LPI geometry parameters. The most important observation from the current study is that the secondary flow in the LPI results in a spatially non-uniform distribution of particles at the exit of the LPI. The particle spatial distribution at the exit is size-dependent, with larger particles being increasingly focused in the central region. If the LPI is operated with a downstream instrument that only detects particles from a subset of the total flow, then the relevant sampling efficiency is seen to be independent of wind-speed ($< 4.5 \text{ m s}^{-1}$) for particles smaller than $20 \text{ }\mu\text{m}$, making this inlet appropriate for use with real-time PM_{10} monitoring instruments. The model predictions of LPI's capability to sample particles as large as $50 \text{ }\mu\text{m}$ must be validated with additional experiments.

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REFERENCES

- Ahlm, L., R. Krejci, E. D. Nilsson, E. M. Martensson, M. Vogt, and P. Artaxo (2010). Emission and dry deposition of accumulation mode particles in the Amazon basin. *Atmos. Chem. Phys.* 10 (21), 10237-10253.
- Belyaev, S. and L. Levin (1974). Techniques for collection of representative aerosol samples. *J. Aerosol Sci.* 5 (4), 325 - 338.
- Brunekreef, B. and B. Forsberg (2005). Epidemiological evidence of effects of coarse airborne particles on health. *European Respiratory Journal* 26, 309-318.
- Fan, B. J., Wong, F. S., McFarland, A. R., & Anand, N. K. (1992). Aerosol deposition in sampling probes. *Aerosol science and technology*, 17(4), 326-332.
- Fang, G.-C., I.-L. Yang, and C.-K. Liu (2010). Estimation of atmospheric particulates and dry deposition particulate-bound mercury hg(p) in Sha-lu, Taiwan. *Aerosol and Air Quality Research* 10, 403-413.
- Faulkner, W. B., Smith, R., & Haglund, J. (2014). Large Particle Penetration During PM₁₀ Sampling. *Aerosol Science and Technology*, 48(6), 676-687.
- Fuchs, N.A. (1964). *The mechanics of aerosols*. Oxford: Pergamon.
- Heist, D. K., Richmond-Bryant, J., Eisner, A., & Conner, T. (2003). Development of a versatile aerosol generation system for use in a large wind tunnel. *Aerosol Science & Technology*, 37(3), 293-301.
- Holsen, T. M., K. E. Noll, G. C. Fang, W. J. Lee, J. M. Lin, and G. J. Keeler (1993). Dry deposition and particle size distributions measured during the Lake Michigan urban air toxics study. *Environ. Sci. Technol.* 27 (7), 1327-1333.
- Holsen, T. M., K. E. Noll, S. P. Liu, and W. J. Lee (1991). Dry deposition of polychlorinated biphenyls in urban areas. *Environ. Sci. Technol.* 25 (6), 1075-1081.
- Kitsa, V., P. J. Liroy, J. C. Chow, J. G. Watson, S. Shupack, T. Howell, and P. Sanders (1992). Particle-size distribution of chromium: Total and hexavalent chromium in inspirable, thoracic, and respirable soil particles from contaminated sites in New Jersey. *Aerosol Sci. Technol.* 17 (3), 213-229.
- Lee, K. W., & Gieseke, J. A. (1994). Deposition of particles in turbulent pipe flows. *Journal of Aerosol Science*, 25(4), 699-709.
- Lee, S., Yu, M., & Kim, H. H. (2013). Development of aerosol wind tunnel and its application for evaluating the performance of ambient PM₁₀ inlets. *Atmospheric Pollution Research*, 4(3).
- Lee, S.-R., T. M. Holsen, and S. Dhaniyala (2008). Design and development of novel large particle inlet for PM larger than 10 μm (PM_{>10}). *Aerosol Sci. Technol.* 42 (2), 140-151.
- Liu, B.Y.H. and Liori, T.A (1974). Aerosol deposition in turbulent pipe flow. *Envir. Sci. Technol.* 8, 351

- Lipiatou, E., I. Tolosa, R. Simo, I. Bouloubassi, J. Dachs, S. Marti, M.-A. Sicre, J. Bayona, J. Grimalt, A. Saliott, and J. Albaiges (1997). Mass budget and dynamics of polycyclic aromatic hydrocarbons in the Mediterranean Sea. *Deep Sea Research Part II: Topical Studies in Oceanography* 44 (3-4), 881 - 905.
- Lundgren, D. A., & Paulus, H. J. (1975). The mass distribution of large atmospheric particles. *Journal of the Air Pollution Control Association*, 25(12), 1227-1231.
- McFarland, A. R., Ortiz, C. A., & Bertch Jr, R. W. (1984). A 10 μm Outpoint Size Selective Inlet for Hi-Vol Samplers. *Journal of the Air Pollution Control Association*, 34(5), 544-547.
- McFarland, A. R., Ortiz, C. A., & Rodes, C. E. (1980). Characterization of sampling systems. *Proceedings, The Technical Basis for A Size Specific Particulate Standard, Part I & II*, 59-76.
- Okazaki, K., & Willeke, K. (1987). Transmission and deposition behavior of aerosols in sampling inlets. *Aerosol science and technology*, 7(3), 275-283.
- Pope, C. A. and D. W. Dockery (2006). Health effects of fine particulate air pollution: Lines that connect. *J. Air & Waste Manage. Assoc.* 56, 709-742.
- Tang, Y., Guo, B., & McFarland, A. R. (2010). A Computational fluid dynamics study of particle penetration through an omni-directional aerosol inlet. *Aerosol Science and Technology*, 44(11), 1049-1057.
- Thomas, J.W. (1958). Gravity settling of particles in a horizontal tube. *J. Air Pollut. Control Assoc.* V8, pp 32-34.
- Tian, L. and G. Ahmadi (2007). Particle deposition in turbulent duct flows comparisons of different model predictions. *Journal of Aerosol Science* 38 (4), 377 - 397.
- Wedding, J. B., McFarland, A. R., & Cermak, J. E. (1977). Large particle collection characteristics of ambient aerosol samplers. *Environmental Science & Technology*, 11(4), 387-390.
- Williams, D. S., M. K. Shukla, and J. Ross (2008). Particulate matter emission by a vehicle running on unpaved road. *Atmospheric Environment* 42 (16), 3899 - 3905.
- Witschger, O., Wrobel, R., Görner, P., & Renoux, A. (1997). A new experimental wind tunnel facility for aerosol sampling investigations. *Journal of Aerosol Science*, 28(5), 833-851.

APPENDIX

Sample calculations of ambient particle concentration from APS data are shown below.

The size dependent LPI sampling efficiency (E_{LPI}) is calculated as:

$$E_{LPI}(D_p) = \frac{LPI_{dn,conc}(D_p)}{WT_{up,conc}(D_p)} \quad (A.1)$$

where $LPI_{dn,conc}$ is the concentration at the exit of the LPI and $WT_{up,conc}$ is the upstream wind-tunnel concentration. The upstream and downstream concentrations ($WT_{up,conc}$ and $LPI_{dn,conc}$, respectively) are calculated from the APS measurements in the tunnel (APS_{up}) and at the exit of the LPI (APS_{dn}) as:

$$LPI_{dn,conc}(D_p) = \frac{APS_{dn}(D_p)}{E_{aniso}(D_p)R(D_p)\eta_{turb}(D_p)} \quad (A.2)$$

$$WT_{up,conc}(D_p) = \frac{APS_{up}(D_p)}{E_{aniso}(D_p)\eta_{turb}(D_p)\eta_{grav}(D_p)} \quad (A.3)$$

where R is the concentration ratio at the exit of LPI, obtained from Figures 9 and 10, E_{aniso} is the anisokinetic enhancement factor, η_{turb} is turbulent deposition loss factor and η_{grav} is the gravitational sedimentation factor.

The anisokinetic enhancement factor, E_{aniso} , is obtained using the empirical expression of Belyaev and Levin (1974) as:

$$E_{aniso} = 1 + \left(\frac{U_\infty}{U_s} - 1\right) \left[1 - \frac{1}{1 + (2 + 0.617 \frac{U_\infty}{U_s}) Stk}\right] \quad (A.4)$$

where U_∞ is the freestream velocity approaching the sampler, U_s is the velocity in the sample tube, and Stk is the particle Stokes number calculated as:

$$Stk = \frac{\tau U_{freestream}}{d_t} \quad (A.5)$$

where τ is particle relaxation time and d_t is the sample tube diameter and η_{turb} are shown below.

Gravitational sedimentation loss in a horizontal circular tube, η_{grav} , is calculated using the expression (Fuchs, 1964; Thomas, 1958):

$$\eta_{grav} = 1 - \frac{2}{\pi} \left[2\varepsilon \sqrt{1 - \varepsilon^{\frac{2}{3}}} - \varepsilon^{\frac{1}{3}} \sqrt{1 - \varepsilon^{\frac{2}{3}}} + \sin^{-1}(\varepsilon^{1/3}) \right] \quad (A.6)$$

where the factor ε is: $\varepsilon = \frac{3}{4} \frac{L}{d_t} \frac{V_{ts}}{U_s}$, where V_{ts} is the particle terminal settling velocity and L is the length of the tube.

Particle penetration through a pipe with turbulent inertial deposition, η_{turb} , is determined as (Lee & Gieseke, 1994; Liu and Iiori, 1974):

$$\eta_{turb} = \exp\left(-\frac{\pi d_t L V_t}{Q}\right) \quad (\text{A.7})$$

where V_t is calculated as:

$$V_t = \frac{V_+}{5.03} \frac{U_{sample}}{Re^{1/8}} \quad (\text{A.8})$$

where V_+ is the non-dimensional deposition velocity: $V_+ = \begin{cases} 6 \times 10^{-4} \tau_+^2 + 2 \times 10^{-8} Re & \text{if } \tau_+ < 12.9 \\ 0.1 & \text{otherwise} \end{cases}$

and τ_+ is the non-dimensional relaxation time: $\tau_+ = 0.0395 Stk Re^{3/4}$.

Data uncertainty calculated using error propagation analysis:

The uncertainty in the calculation of sampling efficiency (σ_{eff}) is estimated considering an error propagation analysis approach:

$$\sigma_{eff} = E \left[\left(\frac{\sigma_{APS_{up}}}{APS_{up}} \right)^2 + \left(\frac{\sigma_{APS_{dn}}}{APS_{dn}} \right)^2 + \left(\frac{\sigma_R}{R} \right)^2 \right]^{1/2} \quad (\text{A.8})$$

where E is the sampling efficiency associated with any APS channel (calculated using Eqn. A.1), $\sigma_{APS_{up}}$ and $\sigma_{APS_{dn}}$ are the uncertainties associated with the APS measurements in a selected channel upstream (APS_{up}) and downstream (APS_{dn}) of the LPI and σ_R is the uncertainty in the calculation of particle concentration enhancements in the LPI exit flow corresponding to the APS location. Note that the uncertainties associated with gravitational and turbulent deposition were neglected in the calculation of the sampling efficiency uncertainty A.8. The uncertainty in the downstream APS measurements was assumed to be the standard deviation of the 1-second particle concentrations recorded during the measurement period (~ 30 minutes). The uncertainty in the upstream APS measurements was considered to be the sum of the standard deviation of the temporal measurements (as in the downstream APS case) and the standard deviation of the spatial distribution (Figure 3). The uncertainty in the particle concentration enhancements (σ_R) was obtained from the standard deviation in the calculated enhancement values for APS probes located at five different locations around the center of the exit flow. The five locations were chosen to be: center of the exit flow and four locations offset from the center of the flow by 1 tube diameter.

List of Figures:

Figure 1 The geometry of the LPI tested in this study: $a = 8\text{cm}$, $b = 4\text{ cm}$, $h_s = 1\text{cm}$, $d_{out} = 4\text{ cm}$, $L = 1\text{m}$.

Figure 2 Experimental setup for generating uniform particle concentrations in the wind tunnel.

Figure 3 Size-dependent spatial variability in particle concentration in the wind-tunnel at the LPI location. In each size channel, the average particle concentrations over the central inlet region are normalized by the average concentration over the entire measurement region. The error bars represent the standard deviation of measurements made at 12 different locations in the vicinity and around the LPI.

Figure 4 Schematic diagram of the experimental setup used for wind-tunnel testing of the LPI

Figure 5 Comparison of experimental data with CFD predictions of LPI sampling efficiencies of Lee et al. (2008). The error bars represent estimated standard deviations in sampling efficiencies. The standard deviations were calculated based on error propagation analysis, accounting for variance in the upstream and downstream concentrations in each size bin over the measurement time period.

Figure 6 Airflow pathlines of LPI at different flow rate and wind speed (a) 1 m s^{-1} 850LPM; (b) 3 m s^{-1} 850 LPM; (c) 1 m s^{-1} 1760LPM; (d) 3 m s^{-1} 1760LPM.

Figure 7 Velocity vectors in the plane perpendicular to the axis of the vertical tube at two locations in the LPI. (a) Just before the flow enters the LPI vertical tube; (b) Near the LPI exit. Note that the lengths of velocity vectors were scaled up to help visualize the nature of the secondary flow in the inlet.

Figure 8 Spatial distributions of particles at the exit of LPI (Sample flowrate: 850 LPM; freestream velocity: $1\text{-}7\text{ m s}^{-1}$) for sizes $3\text{ }\mu\text{m}$ and $50\text{ }\mu\text{m}$. The ambient wind direction is along positive x-direction.

Figure 9 The ratio of particle concentration over the central 10mm area to the average concentration at the LPI exit (original LPI design, $d_{out}=4\text{cm}$ $h_s=1\text{cm}$). The error bars represent the range in the variation of concentration ratio for freestream velocities varying in the range of $1\text{ - }4.5\text{ m s}^{-1}$.

Figure 10 The ratio of particle concentrations in the central 10mm diameter region of the exit flow to that averaged over the entire exit flow for varying h_s and d_{out} at a wind speed of 3 m s^{-1} . The range of h_s and d_{out} values studied are indicated in the legend. The error bar represents the range of concentration ratios for the different geometries studied.

Figure 11 Comparison of experimentally obtained LPI sampling efficiencies with those predicted by different CFD turbulent models for a free stream velocity of 3 m s^{-1} . The error bars for the experimental data represent estimated standard deviations in sampling efficiencies. The standard deviations were calculated based on error propagation analysis, accounting for variance in the upstream and downstream concentrations in each size bin over the measurement time period.

Figure 12 The CFD results for LPI sampling efficiency and wall loss at ambient wind speeds of $1\text{ - }4.5\text{ m s}^{-1}$ ($h_s = 1\text{cm}$, $d_{out}=4\text{cm}$, $Q=1760\text{LPM}$). The LPI sampling efficiency is calculated using two approaches: average particle concentration over the entire exit flow ($\text{Efficiency}_{\text{avg}}$) and particle concentration in a central sub-sample flow ($\text{Efficiency}_{\text{sub-sample}}$). The wall loss is calculated considering the average particle concentration at the exit flow ($\text{Wall-loss}_{\text{avg}}$). The shade regions for $\text{Efficiency}_{\text{avg}}$ and $\text{Wall-loss}_{\text{avg}}$ indicate the range of efficiency and wall loss values over a wind speed range of $1\text{ - }4.5\text{ m s}^{-1}$.

List of Tables:

Table 1: List of parameters used in CFD simulations.

Table 1 List of parameters used in CFD simulations.

	Geometry			Wind speed	CFD package	Number of cells	Near wall refinement	Solver	Turbulent model	Boundary conditions		Particle tracking
	Tunnel	LPI straight section	LPI inlet slit width (h _s)							Type	Turbulent intensity & length scale	
New numerical simulations (current study)	2.5m x 1.2m x 0.9m (L x W x H), rectangular tunnel	d _{out} =4cm L=0.5m; d _{out} =8cm L=0.5m	5mm, 1cm, 2cm, 3cm	1m/s, 3m/s, 4.5m/s, 7m/s	ANSYS Workbench; FLUENT 14.0;	~10M	y ⁺ ~1-2	Explicit	standard k-ε; RSM with enhanced wall function	velocity inlet; outlet-vent; pressure outlet for LPI	1%, 5%; 1m for tunnel, 4cm, 8cm for LPI	Laminar; Stochastic tracking with random eddy lifetime; time-scale constant=0.15
Experiments	1.5m x 1.2m x 0.9m (L x W x H), rectangular tunnel	d _{out} =4 cm L=1m;	1cm	3m/s	-	-	-	-	-	-	-	-
Numerical study (Lee et al., 2008)	0.8mx1.6m circular tunnel	d _{out} =3cm L=0.1m	5mm, 1cm, 2cm	1m/s, 3.5m/s, 7m/s	Gambit; FLUENT6.1.22;	< 2M	y ⁺ ~ 10-25	Implicit	standard k-ε with standard wall function	velocity inlet; outlet-vent; pressure outlet for LPI	5%, 10%; 1cm, 3cm for all boundaries	Laminar

Figure1

Figure2

Figure3

Figure4

Figure5

Figure6

Figure7

Figure8 1m/s 3um

Figure8 1m/s 50um

Figure8 3m/s 3um

Figure8 3m/s 50um

Figure8 7m/s 3um

Figure8 7m/s 50um

Figure9

Figure10

Figure11

Figure12