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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 μm and a cut-size of ~20 μm 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.

1. 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 & Forsberg, 2005; Pope & Dockery, 2006). Particles larger than 10 μm ($PM_{>10}$) 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 $PM_{>10}$ particles aids diffusional-scavenging of carcinogenic material (such as polycyclic aromatic hydrocarbon) and other pollutants (like nitrogen oxides)

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and because of their significant deposition rates, $PM_{>10}$ particles can be a significant source of such pollutants to the Earth's surface.

A common source of dry $PM_{>10}$ 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 $PM_{>10}$ particles will, thus, vary with ambient and source conditions, and must be established from local measurements. The significant inertia of $PM_{>10}$ 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 0.3–100 μm in wind speeds up to 11 km/h. 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, McFarland, and Cermak (1977) and McFarland, Ortiz, and Rodes (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 ~8 μm, with 50% sampling efficiency ~20 μm at a wind-speed of 24 km/h. 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, Guo, and McFarland (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, Holsen, and Dhaniyala (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.

2. Materials and methods

The LPI design of Lee et al. (2008) is shown in Fig. 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 Fig. 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.

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

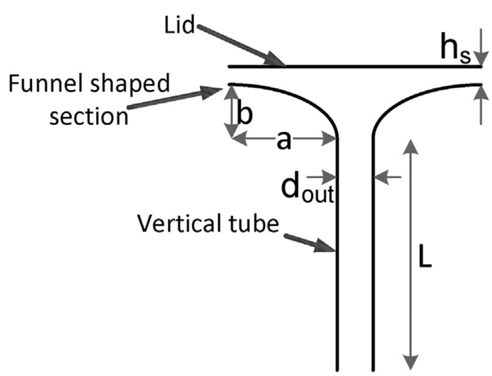

Fig. 1. The geometry of the LPI tested in this study: a=8 cm, b=4 cm, h_s=1 cm, d_{out}=4 cm, L=1 m.