Collection Efficiency of a Personal Cyclone Sampler

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Public exposure to viral agents, especially influenza, is of great concern in workplaces such as schools, office buildings and hospitals. The assessment of personal exposure risk factors in such environments requires efficient and accurate sampling methods valid for both short- and long-term, area and/or personal samples. The National Institute of Occupational Safety and Health (NIOSH) recently developed prototypes for single and two-stage personal aerosol samplers that operate on the principles of a cyclone. The innovative design makes use of commercially available microcentrifuge tubes of various designs that can be attached to the sampler. Since the collection of bio-aerosols takes place in these microcentrifuge tubes, the design has the added advantage of zero transfer losses, hence eliminating the sample transfer step. In the current study Computational Fluid Dynamic (CFD) simulations are performed on both the single and two-stage designs to assess the collection efficiency of the cyclone samplers for various particle sizes and flow rates. Initial validation studies were conducted with particle diameters ranging from 0.5 to 16 µm for the single stage sampler and 0.5 to 6 µm for the two-stage sampler. The inlet flow rates of 2 and 4 LPM for the single stage sampler and 2 and 3.5 LPM for the two-stage sampler were adopted in order to match the experimental conditions. Results showed good agreement with the experimental data for both the single stage and two-stage samplers, thus opening the way to use CFD for virtual sampling in field studies.

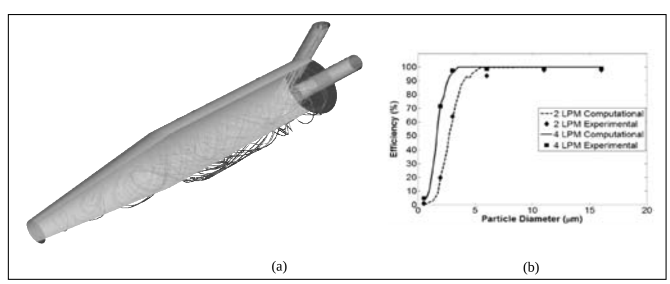
Introduction

Exposure to air-borne microbiological agents can lead to various health problems including allergies, asthma, and most notably, influenza. Because of these health risks, it is becoming increasingly important to investigate human exposure to such bio aerosol agents. In order to accurately assess the risk of personal exposure a sampling method is required that is capable of collecting both short and long term samples over a large area. Unfortunately, most current methods collect only short-term area samples and are not indicative of personal exposure. Current methods for analyzing collected samples involve culturing, where a collected sample is introduced into a culture medium and the resulting growth is analyzed to determine the number of micro-organisms in the sample. Culturing techniques are both difficult and time consuming. A faster technique involves the analysis of collected samples via modern molecular and immunological techniques which use centrifuge machines. Recently the National Institute for Occupational Safety and Health (NIOSH) developed a prototype personal aerosol sampler (Chen *et al.*, 2004 and Lindsley *et al.*, 2006) that employs the principles of cyclone to extract biological particles from the air and deposit them into commercially available micro-centrifuge tubes. The cyclone sampler works by taking in air at an angle to the wall of the micro-centrifuge tube thus creating centrifugal force and pushing the denser particles into the walls of the tube which eventually settle at the bottom of the tube. This personal sampler is compact enough to be worn during the course of a full day, allowing assessment of total individual exposure. In addition to allowing for spatially variable samples, the NIOSH design totally eliminates transfer losses during analysis because the particle collection occurs in the micro-centrifuge tubes. A two-stage sampler that allows for collection of size-segregated samples was also recently developed at NIOSH. This design makes it possible to separate different microbiological species based on their individual aerodynamic properties. In the current study we apply Computational Fluid Dynamics (CFD) techniques to characterize the flow through both the single and two-stage cyclone samplers and assess collection efficiencies for a range of particle sizes at different inlet volume flow rates. It is the goal of this study to develop and validate virtual CFD samplers. We also demonstrate the advantages of CFD which allows for fast and inexpensive testing of sampler prototypes at different flow conditions and particle sizes, and most importantly, identify new design parameters for future cyclone samplers.

Methodology

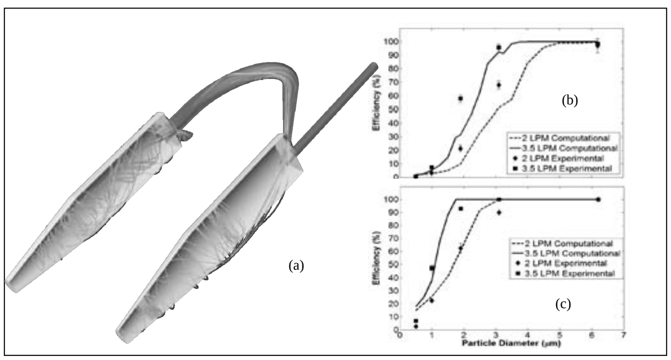
GAMBIT (Fluent Inc. Lebanon, NH) was used to build a grid to geometric specifications for each of the prototype samplers. The single stage sampler (Chen *et al.*, 2004) consisted of a cylindrical section 24.48 mm long and 8.27 mm in diameter, a conical section 19.09 mm in length with a tip diameter of 2.99 mm. The tangential inlet tube is 1.99 mm in diameter and the outlet tube has a diameter of 2.24 mm. The computational grid used for single stage sampler contained 781000 cells (Figure 1).

Figure 1. (a) particle trajectories for 3 µm particle at 2LPM and (b) computed collection efficiency compared to experiments (by Chen et al., 2004) for the single-stage sampler.



The 3-D, steady, incompressible flow was solved using FLUENT (Fluent Inc. Lebanon, NH) for inlet volumetric flow rates of 2 LPM and 4 LPM. The fluid was modeled as air at 1 atm and 287.5 K (Standard conditions). The flow was considered laminar for both the 2 LPM and the 4 LPM cases based on inlet Reynolds numbers, 1460 and 2920 respectively. Once the continuous phase was resolved, the Discrete Phase Model (DPM) was used to solve for the trajectories of particles ranging in size from 0.5 μm to 16 μm. Because all of the particles being considered in this study were in the micron range, their effect on the fluid is neglected during calculation of particle trajectories. The two-stage sampler (Lindsley *et al.*, 2006) had the same dimensions for the cylindrical and conical sections but the inlet and outlet tube diameters are different. The inlet tube to the first stage has a diameter of 2 mm. The outlet of the first stage has a diameter of 3 mm (this larger diameter limited the undesirable collection of biological material in the connecting tube) that tapers down to 1.3 mm at the inlet to the second stage (see Figure 2). The final outlet has a diameter of 1.5 mm. The grid used for the

Figure 2. (a) particle trajectories for 2 μm particle at 3.5LPM and computed collection efficiency of (b) first stage and (c) second stage compared to experiments (by Lindsley et al., 2006) for the two-stage sampler.



two-stage sampler contained 1.5 million cells. For the two-stage sampler inlet volumetric flow rates of 2 LPM and 3.5 LPM were used The flow is considered to be laminar for both the 2 LPM and the 3.5 LPM cases based on their inlet Reynolds numbers, 1453 and 2544 respectively. The Discrete Phase Model was used to solve for the particle trajectories, with particle sizes ranging from 0.5 μm to 6 μm.

*Collection Efficiencies.*To find the number of particles collected in each of the samplers, wall boundary conditions were applied to the sampler (cylindrical and conical sections) walls, the inlet tube walls, the outlet tube walls, and the connecting pipe walls (only for the two-stage sampler). The DPM will cause the termination of the particle trajectory when it is in contact with any of these walls in the sampler. Once the particle trajectories are calculated for a certain particle, the collection efficiency of the sampler for that particle and flow rate is calculated by dividing the number of particles collected in the specific tube by the number of particles collected there and after in the sampler.

Results and Discussion

The two most important design parameters for sampler are the collection efficiency distributions for different particle sizes and the d_{50} cut-off diameter (particle diameter which results in a 50% collection efficiency). The computed collection efficiency of the single stage sampler for various particle diameters and flow rates agree very well with the experiments by Chen *et al.* (2004). The d_{50} cut-off for the 2 LPM and 4 LPM cases were found to be 2.7 μm and 1.6 μm respectively, which is in good agreement with the 2.5 μm and 1.5 μm values reported by Chen *et al.* (2004). Figure 2 shows the computed collection efficiencies for the 1st stage collection tube and the 2nd stage collection tube of the two-stage sampler compared to the experimental values reported by Lindsley *et al.* (2006). For the 1st stage collection tube the d_{50} cut-off diameters for the 2 LPM and 3.5 LPM cases were calculated to be 3.1 μm and 2.3 μm respectively. These computed values are slightly higher than the 2.6 μm and 1.8 μm values for the 1st tube reported by Lindsley et al. (2006). For the 2nd stage collection tube d_{50} cut-off diameters for the 2 LPM and 3.5 LPM flow rates were calculated to be 1.7 μm and 1.1 μm respectively. These values agree well with the 1.6 μm and 1.0 μm values identified by Lindsley *et al.* (2006) for the 2nd stage collection tube. The relatively small discrepancy between the experiments and the computations are believed to be due to inherent modeling errors (i.e. approximations in governing equations of motion). The difference between three different DPM's employed was in the order of the error between the experiments and the computations. Conclusions: The results of the current study show that CFD can be used to accurately predict collection efficiencies for a wide range of particle sizes, as well as the d_{50} cut-off diameters for different inlet volumetric flow rates. The ability of the two-stage sampler to collect size segregated samples can also be accurately modeled using the current CFD techniques. Our study shows that CFD techniques can be used to virtually sample field data and test different design parameters and conditions for new samplers.

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