Final Report

John Volckens (PI)
Colorado State University
Fort Collins, CO 80523
T: 970-491-6341
John.Volckens@colostate.edu

Project Title: A Portable Spectrometer for Inhalable Aerosol Size Distributions

Project Dates: 07/01/2012 - 06/30/2015

NIOSH Grant #: R21OH010117

Report Date: 10/26/2015

Table of Contents

Abstract

Accurate measurement of inhalable aerosol hazards has confounded occupational health professionals since the realization that particle size plays a primary role in determining aerosol penetration into (and deposition within) the human respiratory tract. Knowledge of particle size not only determines whether a particle can enter the body and where it will deposit (oronasal vs. tracheobronchial vs. pulmonary regions) but also influences the process of hazard recognition, evaluation, and control. For example, knowing the size distribution of an aerosol hazard can reveal its source: submicron particles (<1 µm) tend to arise from vapor condensation or combustion processes, whereas, supermicron particles (>1 µm) are typically generated from abrasive, mechanical processes. Furthermore, the design and use of proper workplace control technologies (filtration, cyclone separation, ventilation) are strongly dependent on knowledge of particle size.

Despite these facts, the field of occupational health lacks the technology to determine the size distribution of inhalable aerosol hazards in the workplace. Indeed, industrial hygienists currently have no means to characterize workplace aerosol size distributions above 15 microns, even though the current ACGIH/ISO criterion for inhalable aerosol extends to 100 microns in particle diameter. Many practicing professionals suspect that such particles present a significant respiratory hazard in their workplaces. Yet, the same professionals lack tools to characterize such hazards – a limitation that substantially hampers their ability to protect workers at risk. Inhalable aerosols hazards are present in virtually every NORA sector: organic dusts in agriculture, forestry, and fishing; carbonaceous and mineral dusts in construction; metal and metalworking fluid aerosols in manufacturing; and coal dust in mining, to name just a few. This project developed a new instrument to meet this need and to characterize workplace aerosol size-distributions up to 100 microns.

Section 1

Significant (Key) Findings.

Key Finding #1: The upflow elutriator design combined with virtual impactor theory holds promise to advance the state of the art in occupational exposure assessment for characterizing the size-distribution of inhalable aerosols. This research lead to the development of two instruments capable of measuring the size-distribution in occupational environments.

Key Finding #2: Both instruments were capable of size-segregating particles, however, the vPIPS had sharper cutoff curves and higher sampling efficiencies than the original PIPS design.

Translation of Findings.

The development of the PIPS and vPIPS samplers are capable of characterizing the size-distribution of inhalable particles in the workplace, giving industrial hygienists and exposure scientists a tool to evaluate a hazard that has been, up until now, difficult to quantify.

Outcomes/Impacts.

In this project we developed two instruments for characterizing the size-distribution of large inhalable particles (10 to 100 microns). A potential outcome from this work is that these instruments will allow the evaluation of hazards that have not been quantified to date. Understanding the size distributions in workplaces will allow for better selection of control methods, improved exposure assessments and epidemiological studies, and improve worker health. Once this instrument is commercialized, it will enable occupational health professionals to assess inhalable aerosol hazards more fully, as no commercially-available technologies currently exist to meet this need. This technology will also enable the determination of size-specific chemical composition, as it will integrate into an existing analytical framework, namely: aerosol collection and analysis onto sampling filters. This research produced one published manuscript in the peer-review literature, three conference abstracts, one M.S. Thesis, one career development award, and one patent.

Section II. Scientific Report

The goal of this project was to develop new technology to characterize the size distribution of inhalable aerosol hazards in the workplace. Our approach used the theory of an up-flow clarifier to take advantage of large particle settling velocities to size-segregate airborne particles accurately and precisely for determination of inhalable aerosol size distributions between 10 and 100 microns. Our proposed instrument was a series of single collection tubes, each with different airflows, to size-segregate particles. We achieved this aim and demonstrated the feasibility of the original proposed design. In addition to the original design, we developed a second instrument, the vPIPS sampler, that combined the upflow clarifier of the PIPS with a modified virtual impactor to achieve sharper cut points. This project had three specific aims; progress for each aim is discussed below.

Aim 1: Design an inexpensive, upflow clarifier to characterize the size distribution of inhalable aerosol hazards in the workplace (ranging from 10 to 100 µm).

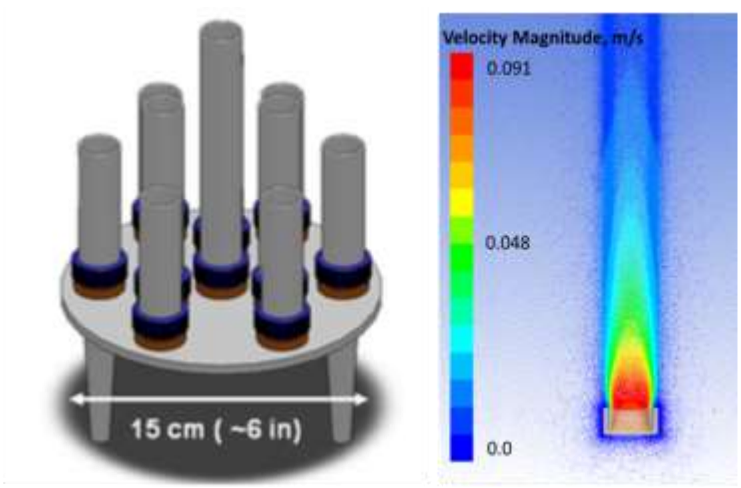

Figure 1: (left) Original design schematic of the multi-tube PIPS. (right) CFD modeling of airflow exiting the a PIPS tube revealed the presence of a laminar jet that affected particle sampling efficiency.

Aim 1 sought to develop the instrument design based on inhalable particle theory. Computational fluid dynamics (CFD) modeling was used to optimize the instrument performance. We initially proposed an instrument (Figure 1) with a series of flow tubes, each based on the size-segregation principle outlined above, but of varying flow/velocity, as outlined in Table 2. Five different velocities are employed (two tubes for each velocity) to segregate particles into ranges of: d_p >10 µm, >20 µm, >40 µm, >60 µm, >80 µm. We developed a prototype sampling tube and tested it experimentally at cut sizes of 30, 40, 50, 60, 70, and 80 microns. However, initial experimental testing using a single flow tube and velocity showed the presence of a jet at the top of the collection tube inlet, confirmed by CFD modeling. This "jet effect", shown in Figure 1 at right, resulted in non-sharp cut points and further would have made arranging multiple tubes next to each other impractical as particles ejected from one tube would interfere with sampling at adjacent tubes. Thus, we developed a second sampler design to eliminate the jet at the top of the collection tube that was not in the original proposal.

The second design (shown in Figure 2), as with the original PIPS design, utilizes an upward flow of clean air through a filter/collection tube combination. However, the PIPSv2 sampler (also known as the vPIPS) has a cap with a round inlet opening that is centered directly above the collection tube. Below this cap, air coming from the collection tube is pulled radially outward into an annular space between the cap and tube walls, and from there out the bottom of the sampler. This exhaust flow is set to equal the upward flow through the collection tube so that no air enters the sampler through the cap inlet opening. As the upward flow from the collection tube bends radially outward, it forms an axial stagnation point below the cap inlet. From this stagnation point, smaller particles that fall through the cap inlet opening are carried away with the radial, outward flow whereas larger particles fall into the collection tube. This design eliminates the jet that emanates from the top of the collection tube and should improve the sharpness of the resultant cutoff curve. The second sampler design, PIPSv2, was tested in the calm air chamber at 7 cut sizes (30, 40, 50, 60, 70, and 80 microns). The CFC modeling results indicated the new design would reduce the jet effect at the inlet and result in much sharper cutoff curves. Therefore, both sampler designs were moved forward in Aims 2 and 3.

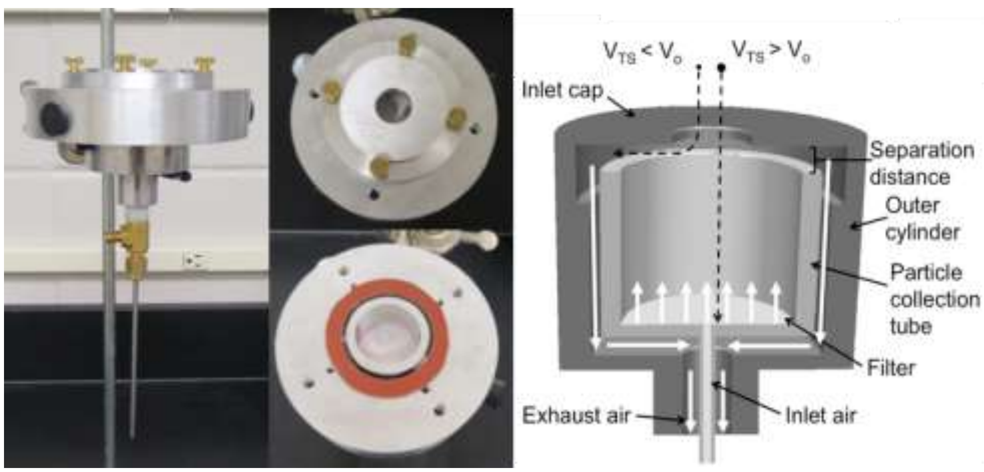

Figure 2: Prototype PIPSv2 and (left) design schematic (right)

Aim 2: Evaluate device performance using a combination of calm-air chamber studies and low- velocity wind tunnel experiments.

Aim 2 tested both the PIPS sampler and the vPIPS sampler in the calm air chamber at Colorado State University. Sampling efficiency for each cutsize (30, 40, 50, 60, 70, and 80 microns) was measured. The polydisperse test powder was fluorescent, polyethylene microspheres of unit density with sizes ranging from 10 to 90 microns (UVYGPMS, Cospheric LLC). An epi-fluorescent microscope (Orthoplan, Leica) and fluorescence filters (Vivid Plus Set XF05-2/B, Omega Optical) were used to image collected particles. Filters were imaged under a 1.6x objective lens and a 10x objective eyepiece. ImageJ software (NIH, V1.46r (Rasband)) was used to obtain the area of each particle, from which the corresponding particle aerodynamic diameters were calculated using Microsoft Excel. A stage micrometer provided a reference for ImageJ size analysis. Size distributions of the reference samplers were measured using microscopic analysis following the procedure outlined above. Particles were sorted by aerodynamic diameter into one of nine size bins from 15 to 95 microns, each with a 10-micron bin width. Low-velocity wind tunnel studies and calm-air sampling performance of the PIPS and vPIPS were simulated using computational fluid dynamics modeling (CFD) to evaluate the effect of windspeed on sampling efficiency.

The experimental and simulated sampling efficiency curves at the six cut points for the PIPS and PIPSv2 samplers are displayed in Figure 3. The error bars in this figure represent one standard deviation based on the variability between sampling efficiency measurements for repeated experiments. The experimental PIPS sampler efficiency showed good agreement with the CFD model. As particle size increased, the measured PIPS sampler efficiency deviated more from the simulated sampling efficiency: the cut point became less sharp, and measured sampling efficiency for particles larger than the cut size was less than 100%. Experimental sampling efficiency was substantially higher than the simulated sampling efficiency for the 80 micron cut. Although the PIPS sampler was predicted to perform reasonably well, particle separation curves were not as sharp as desired and the sampling efficiencies were less than 100% for particles larger than the cutsize.

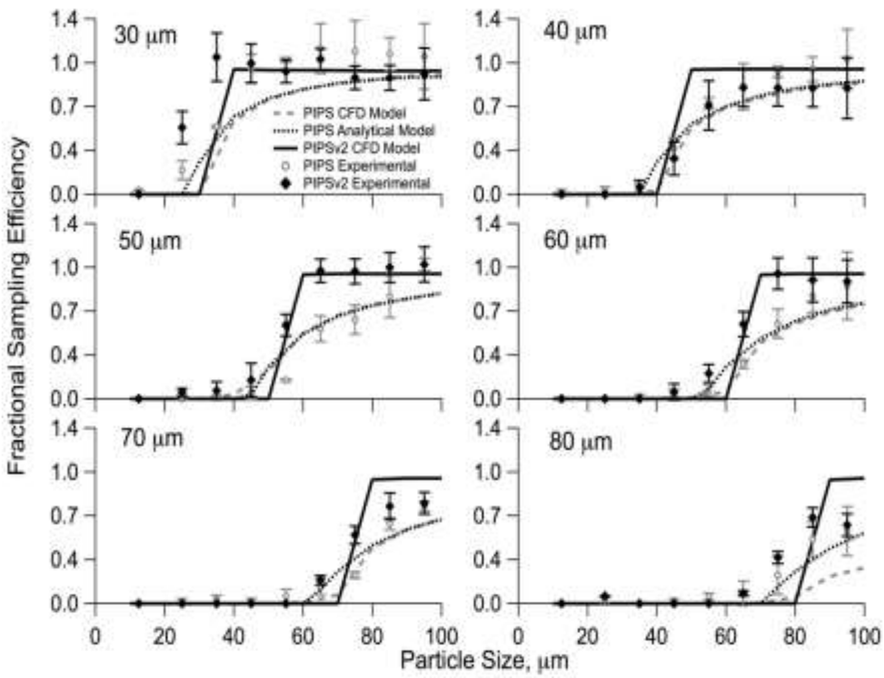

Figure 3: Sampling efficiency curves for PIPS and PIPSv2 samplers

The PIPSv2 sampler was designed to minimize the jet effect at the top of the PIPSv2 collection tube while maintaining a flat velocity profile throughout the tube. Experimental sampling efficiency for the PIPSv2 sampler compared reasonably well to CFD simulations (Figure 3). The 70 and 80 micron cuts had the greatest differences between experimental and simulated efficiencies, with experiments underestimating simulated sampling efficiencies by 20 to 30% for particles larger than the cut size. The PIPSv2 sampler had much higher sampling efficiencies and steeper cuts than the PIPS sampler, especially for the 50 and 60 micron cut points. The CFD modeling also revealed the presence of the upward jet emanating from the PIPS sampler (Figure 4), further confirming the need for the radial outward flow seen in the vPIPS.

A data inversion was developed to estimate a continuous size distribution from measured particle discrete particle counts each size bin. A logistic function was fitted to the sampling efficiency curves for each cut point. The coefficients were obtained by nonlinear, least-squares regression. Next, an initial approximation of a count median diameter (CMD) of 52 microns and standard deviation (SD) of 15 microns were used as a random starting point; these CMD and SD values were then adjusted through a series of iterations to arrive at the optimal solution. A data-inversion spreadsheet was developed in Microsoft Excel (2010, Microsoft Corp., Seattle, WA) to estimate the CMD, SD, and number concentration of a normally distributed, unimodal aerosol from particle number concentrations measured with the PIPS sampler at six cutpoints following the method described by O'Shaughnessy and Raabe (O'Shaughnessy and Raabe 2003).

The data inversion procedure worked reasonably well (Figure 4). Both samplers characterized the CMD and standard deviation reasonably well, although the PIPS sampler somewhat overestimated the CMD.

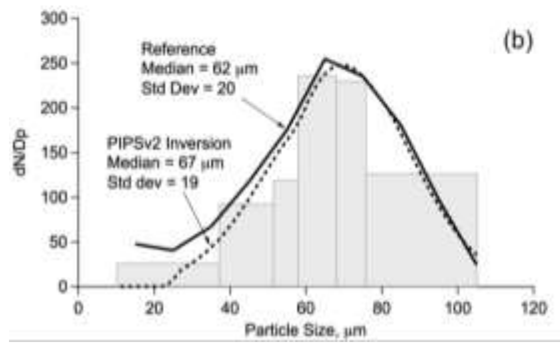

Figure 4: PIPSv2 size distribution using data inversion procedure

Aim 3: Test sampler performance in the field by characterizing inhalable particle size distributions for organic dust hazards in dairy and grain handling facilities.

The goal of aim 3 was to test the sampler in the field in dairy. This aim was not completed due to the duration of Aims 1 and 2. However, this aim will continue as part of the Career Development Award (K01OH010763) for Dr. Kim Anderson, the postdoc who worked on this R21 project. Dr. Anderson's work is underway. She will incorporate real-time detection into the PIPSv2 sampler, which would make the instrument more applicable to field applications. Thus, field work will follow from completion of the real-time detection component within the vPIPS.

Published Papers

Anderson KR, Leith D, Ndonga M, and Volckens J (2015). *Novel Instrument to Separate Large Inhalable Particles.* Aerosol Science and Technology (accepted, in press).
DOI: 10.1080/02786826.2015.1112874

Conference Presentations

Kimberly Anderson, Sean Walsh, Azer Yalin, John Volckens, "Design and Optimization of an Optical Detector for the Portable Inhalable Particle Sizer," oral presentation, American Association of Aerosol Research (AAAR), Minneapolis, MN, October 2015.

Kimberly Anderson, Dave Leith, Sean Walsh, Jordan Rath, Azer Yalin, John Volckens, "Design and experimental testing of an inhalable particle spectrometer," oral presentation, American Association of Aerosol Research (AAAR), Orlando, FL, October 2014.

Ndonga, M., and J. Volckens. "Characterizing Inhalable Size Distributions in the Workplace," oral presentation, Mountain and Plains ERC Annual Research Day, Loveland, CO, March 2013.

Patents

Volckens, J. et al. "Portable Particle Spectrometer." United States Patent Application 14/918,798. Filed on October 21, 2015.

Graduate Theses

Ndonga, M. "DESIGN OF AN INHALABLE AEROSOL SIZE SPECTROMETER" M.S. Thesis in Environmental Health (Industrial Hygiene Specialization). Colorado State University. December 2014.