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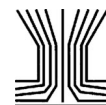
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Performance of two shrouded probes for the collection of liquid aerosols in a wind tunnel optimized for high air speeds

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ABSTRACT

A combination of type A (high flow model) or B (low flow model) shrouded probe and appropriate isokinetic air-sampler (IAS) was tested in a wind tunnel that was optimized for high air speed testing using computational flow modeling. Liquid uranine aerosols (LUA) with AED (aerodynamic equivalent diameter) of 10 μm were generated at a constant flow rate using a vibrating orifice aerosol generator. The monodispersed aerosols were introduced into a wind tunnel at speeds of 5, 10, 15 and 20 m/s. The high flow (A) or low flow (B) model shrouded probe and the appropriate isokinetic air-sampler (IAS) was co-located to collect the LUA simultaneously during each treatment. After the test, the LUA deposited on the filters and inside the walls of the two air-samplers were collected and analyzed for fluorescence intensity units to determine the wall loss, transmission and aspiration ratios. While the type B shrouded probe had 20% (at 10 m/s) and 14.3% (at 15 m/s) higher wall loss ratios than model A, it had 16.1% (at 10 m/s) and 11.6% (at 15 m/s) higher transmission ratios compared to model A. Similarly, probe B had 17.6% (at 10 m/s) and 14.6% (at 15 m/s) higher aspiration ratios than probe A at similar air velocities. Overall, the wall loss, transmission and aspiration ratios of 10 μm AED ULA measured with two types of shrouded probes at 5, 10, 15 and 20 m/s air velocities in the optimized wind tunnel had good agreement with the range of standard data.

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Introduction

It is important to measure the $\text{PM}_{2.5}$ (mainly fine and ultrafine) particle concentration around nuclear energy plants as they have a large impact on the human body and environment. Various forms of very high airflow samplers are being installed around these plants in different places in the world to gather, and analyze radioactivity, control aerosol samples and prevent nuclear accidents. The Environmental Protection Agency (EPA) prescribed methodologies for sampling not only the suspended particles in ambient air (outdoor and indoor), but also radionuclides in air effluents from stacks and ducts of energy producing facilities. These methodologies explain how to find the sampling locations, estimate the number of samplers, and use the guidance of the American National Standards Institute (ANSI/HPS N13.1 1999/2011) to design shrouded sampling probes at a specified site. Among various

air samplers used to determine the real concentrations of very small (0–20 μm) aerosols (mainly nuclides) in the duct, the shrouded samplers showed very high particle transmission from a moving air-stream in the wind tunnel. McFarland et al. (1989) developed the first shrouded air sampler with a 30-mm-diameter probe located concentrically within a 105-mm-diameter tube (as a covering pipe) with the constant airflow rate of 0.0028 m^3/s . ANSI recommended the use of a shrouded air sampler with a sharp-edged elbowed-nozzle and multi-probe rake. However, it had substantial losses of aerosol particles, and was not able to estimate the quality of emission from a nuclear facility. Later McFarland and Rodgers (1993) replaced this shrouded air sampler with a single probe to reduce the wall losses of aerosol particles and gain more representative aerosol in the filter, because the single probe assures the mixing of contaminant mass and fluid momentum at the sampling location. Ram, Cain, and Taulbee

(1995) and Cain, Ram, and Woodward (1998) tested the shrouded air sampler for the high velocity air-borne aerosols in the size of 0.1–15 μm in the wind tunnel and verified the fluid dynamics design by calculating the airflow and the aspiration efficiency of the shrouded probes. Later Sippola and Nazaroff (2014) changed the cylindrical shape of probe (in shrouded air samplers) to an isokinetic design. They compared this new design with a buttonhook isokinetic nozzle at a constant low flow rate (2.2–8.8 m/s) and reported that the probe with an isokinetic shrouded nozzle had higher particle transmission than the other nozzles for sampling particles in a wind tunnel.

Overall, the results of any design of shrouded air samplers in the wind tunnel are valid as long as the testing conditions are matched with the following test criteria of EPA and ANSI standards (Cheng et al. 2004):

1. The particle delivery system shall consist of a blower system and a wind tunnel having a test section of sufficiently large cross-sectional area such that the cross sections (shrouded and/or isokinetic) of air samplers, as installed in the test section for testing, blocks no more than 15% of that area.
2. To be acceptable, the blower system must be capable of achieving uniform wind speeds (for example 2 (0.56), 8 (2.22) and 24 km/h (6.67 m/s)). The mean wind speed in the test section must be within $\pm 10\%$ of the values mentioned above.

While the conventional form of shrouded and isokinetic air samplers was used in different tests, it had a noticeable wall loss of aerosol. Later different parts of the conventional sampler including shrouded support, bypass flow, and inner probe with gradual or sudden enlargement were redesigned to reduce the wall losses and increase the collection ratio for particles on its probe (in comparison with the isokinetic air sampler; ANSI/HPS N13.1 (1999/2011)).

Recently two models of shrouded air samplers (Model A or Model B, labeled as RF-2-111 or FR-2-112 by the manufacturer LabWorks Inc., respectively) have been designed to capture nuclides generated at energy facilities at high air volumes with maximum efficiency and minimum wall losses.

Since liquid particles (such as uranine aerosols) adhere to any walls of air samplers that they strike, they provide a conservative assessment of aerosol transmission (McFarland and Rodgers 1993). Wall losses for the shrouded probes were generally one-half of those in the unshrouded (isokinetic) samplers, ranging from 11.4% to 19.3% and from 21.2% to 28.1% for 10 and 15 μm liquid particles, respectively (Chandra and McFarland 1995). Sampling efficiency and transmission and wall loss ratios are dominated with particle inertia. Wall losses increase with particle size and therefore if an acceptable performance is established at 10 μm , it is expected that the performance of the shrouded probes will be acceptable also at smaller sizes, including 2.5 μm .

The objective of this study was to evaluate the performance of these shrouded air samplers along with the appropriate isokinetic reference air samplers in an optimized wind tunnel at the wind speeds of 5, 10, 15 and 20 m/s, with 10 μm uranine particles generated and mixed uniformly with the airstream in the wind tunnel.

Methodology

Wind tunnel optimization using computational fluid dynamics modeling

The wind tunnel used for this study was originally fabricated in 1980 (McFarland and Ortiz 1984) and set up at the Center for Agricultural Air Quality Engineering and Science (CAAQES) – Aerosol Technology Laboratory at Texas A&M University. Since this wind tunnel was designed originally to evaluate the performance of PM_{10} and TSP air samplers, different changes were made to make it capable for testing two types of single-point shrouded air samplers (A or RF-2-111 and B or RF-2-112) along with appropriate isokinetic air samplers (A or B) at 5, 10, 15 and 20 m/s wind speeds. The internal diameters (ID) of shroud and probe in RF-2-111 (high flow model A) were 54.15 and 18.5 mm, respectively (Figure 1). Similarly, the IDs of shroud and probe in RF-2-112 (low flow model B) were 54.15 and 34.81 mm, respectively. The recommended air velocity ranges for both of these air samplers were 0–18 m/s (Su and Vincent 2004).

The new design of the TAMU wind tunnel (Figure 2) sequentially consists of one cylindrical

duct (with 0.36 m diameter and 0.94 m length), two rectangular parts with square cross sections (each one with 0.61 m x 0.61 m square cross section and 1.22 m length), one gradual contraction from the square to elliptical cross section (with 0.56 m length), one elliptical duct (with 0.15 m small diameter, 0.33 m large diameter and 0.94 m length), and finally one rectangular part (with 0.61 m x 0.61 m square cross section and 1.22 m length) used for mounting air samplers, a high efficiency particulate air (HEPA) filter, blower and a variable frequency drive (VFD) of 60 Hz. The NYB blower (Model 7103, The New York Discharge Blower Company) located at the end of wind tunnel has a capacity to draw up to 2.2 m³/s of air.

A carefully designed inlet bell mouth (known as the “contraction”) and a flow straightener built between the first two rectangular parts of wind tunnel were employed to minimize the lateral velocity components caused by the swirling motion in the entering air flow. The particle losses in the wind tunnel were estimated based on the collection of the generated liquid particles that had a higher concentration when the flow straightener was present. Computational airflow modeling of the wind tunnel configuration with the flow straightener showed less vortices in the airflow that could result in reduced particle deposition and wall losses.

A HEPA filter was fitted at the last rectangular section to capture uranine particles at the end of the wind tunnel and prevent air contamination (Faulkner, Smith, and Haglund 2014). A portable hot film thermal anemometer (Model 8360, TSI Inc., Shoreview, MN, USA) was installed at the exit of the ellipsoid duct to measure wind velocity and adjust the air speed by changing the VFD controller of the discharge blower. The VFD was set at 8.25, 16.85, 23.40 and 29.05 Hz to generate wind speeds of 5, 10, 15 and 20 m/s, respectively. There was no blockage or “hot swapping” of airflow due to the location of different shrouded and isokinetic air samplers in the wind tunnel. The total cross section areas of these air samplers were less than 50 cm², and its ratio to cross-section of the elliptical exit of wind tunnel was about 0.1 or 10%. According to USEPA (2017) mentioned in 40 CFR 53.42, the candidate air samplers used in the wind tunnel are acceptable as long as their blockage (or volume) ratio is less or equal to 15% of test section.

Computational fluid dynamics (CFD), pioneered a century ago by Richardson (1911), has gained popularity recently and has revolutionized the way products are designed and manufactured (Xia and Sun 2002). Many different CFD software platforms have

been developed and become more powerful each year. There have been many debates about the various CFD platforms, and their computational proficiency. Some studies have calculated the amount of fresh air delivered and contamination removed by tracking airflow in the room, such as the study by Rouaud and Havet (2005), whose experimental results showed contamination of a room is largely dependent on the location of initial contamination. They displayed contaminant removal effectiveness equations to garner the efficacy of ventilation systems, and used the room mean age of air to determine mean decontamination time.

The most widely used design software in education and industry today, the SOLIDWORKS® Flow employs the Navier-Stokes equation (Equations (1) and (2)) in conjunction with a finite volume discretization that divides the computational domain into elementary volumes around every node in the grid, ensuring the flow between nodes is continuous. Tetrahedral interpolation is used for spatial discretization, while temporal discretization utilizes the implicit formulation.

The generic form of the Navier-Stokes Equation (Velocity and Pressure component is compressed) is shown below:

$$\frac{\partial}{\partial t} u + \Delta \cdot uu = -\frac{1}{\rho} \Delta p + \nu \Delta^2 u \quad (1)$$

The expanded Velocity and Pressure Component can be expressed as:

$$u = u_{avg} + u'$$

$$p = p_{avg} + p'$$

Where,

u_{avg} = average velocity component (m/s)

u' = fluctuating velocity component (m/s)

Applying the averaging to the expanded Navier-Stokes Equation yields:

$$\begin{aligned} \frac{\partial}{\partial t} u_{avg} + \Delta \cdot u_{avg} u_{avg} &= -\frac{1}{\rho} \Delta p_{avg} + \nu \Delta^2 u_{avg} + \Delta \langle u'u' \rangle \\ &\quad \langle u'u' \rangle \quad \langle u'v' \rangle \quad \langle u'w' \rangle \\ \langle u'u' \rangle &= \langle u'v' \rangle \quad \langle v'v' \rangle \quad \langle v'w' \rangle \\ &\quad \langle u'w' \rangle \quad \langle v'w' \rangle \quad \langle w'w' \rangle \end{aligned} \quad (2)$$

SOLIDWORKS® Flow uses an empirical, modified two equation $k-\epsilon$ turbulence model along with immersed boundary Cartesian meshing that allows a wide range of turbulence models to be calculated correctly with the utility of low-density mesh sizes. In these equations K is the kinetic energy and F is the dissipation rate of turbulent energy. The $k-\epsilon$ model has been used effectively to model room airflow, including forced convection (Chen and Moser 1991; Beck et al. 2019). An alternative to this method is the Large Eddy Simulation (LES) model that has received much attention and is capable of calculating real time turbulent flow, as opposed to the steady state solution found by the $k-\epsilon$ model.

Shrouded probes model A (RF-2-111) and model B (RF-2-112)

The commercial shrouded probes Model A (RF-2-111) and Model B (RF-2-112), shown in Figure 1 were mounted isoaxially at the exit of the elliptical nozzle in the mid-section of the aerodynamic wind tunnel at the angle of zero degrees relative to the flow (Figure 2). Flow field data such as velocity and turbulence intensities at the entrance of the probe were measured with the hot film anemometer (TSI Inc., Burnsville, MN, USA).

The 7.6 mm isokinetic probe RF ISO 1 and the 13.4 mm isokinetic probe RF ISO 2 were used at different air velocities (Table 1). The shrouded probe Model A and Model B were tested at 57 L/min flow rate.

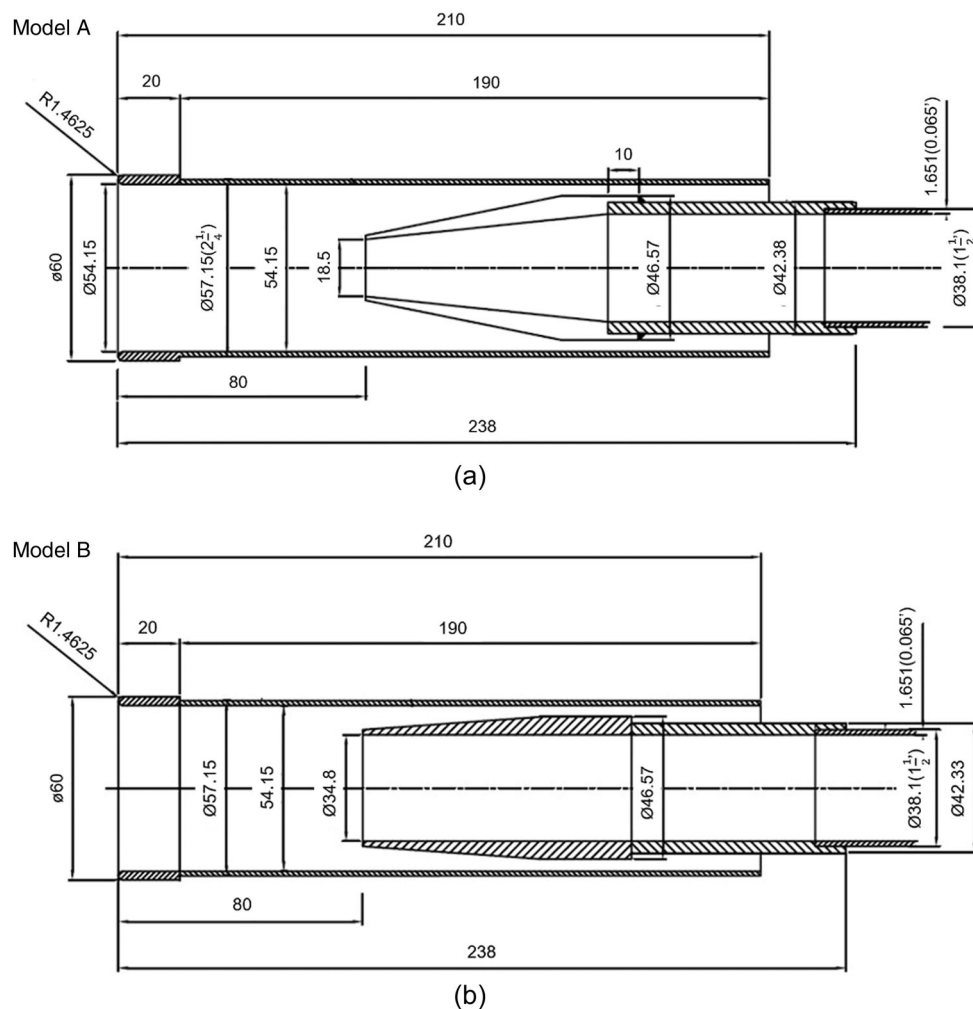


Figure 1. The drawings of the shrouded probe Model A (RF-2-111) and Model B (RF-2-112). All dimensions are in millimeters (mm). Tolerances: $x \pm 0.10$ mm.

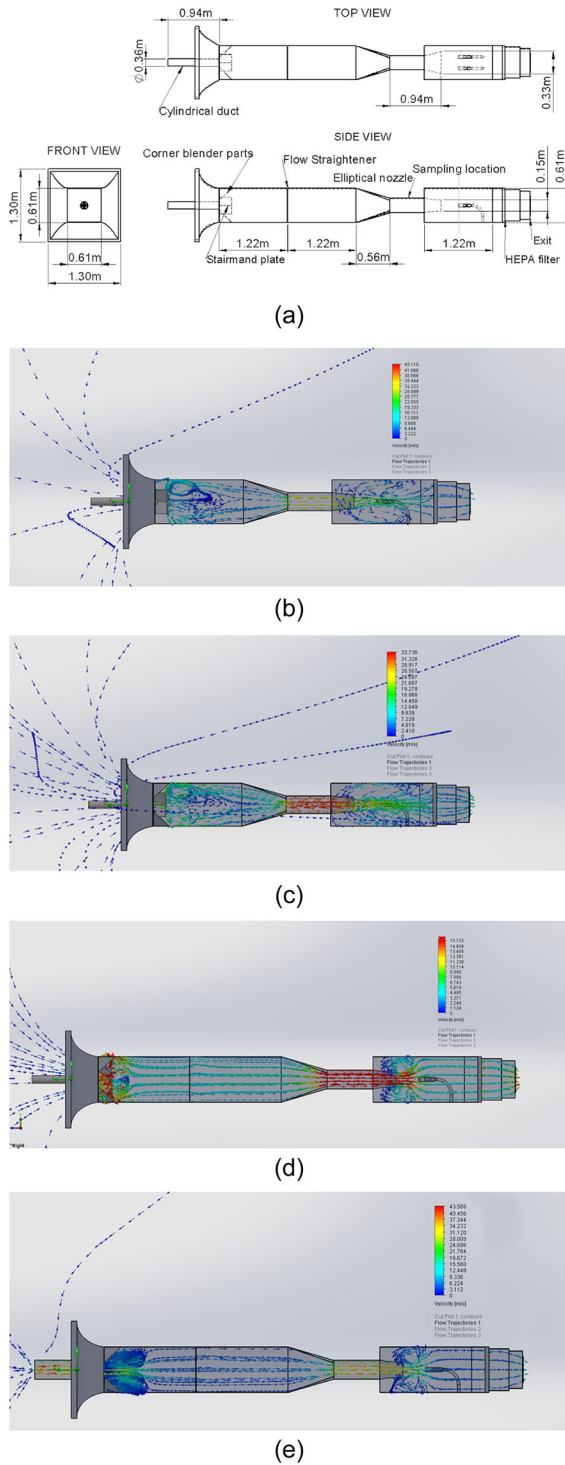


Figure 2. The optimization of the high-speed wind tunnel based on four consecutive modifications. (a) Schematic of the wind tunnel configuration with the Stairmand plate, corner blender parts, flow straightener and elliptical nozzle; (b) flow model of the original design with the second $0.61\text{ m} \times 0.61\text{ m} \times 1.22\text{ m}$ segment removed and elliptical nozzle inserted in the middle; (c) flow model of the wind tunnel with corner blender parts added; (d) flow model after removal of the Stairmand plate and the insertion of an additional $0.61\text{ m} \times 0.61\text{ m} \times 1.22\text{ m}$ segment; (e) addition of a circular (cylindrical) inlet at the entrance and a flow straightener between the first two segments. The flow simulations for all the wind tunnel configurations were created at the nominal air speed of 15 m/s .

Preparation and generation of liquid uranine aerosols (LUA)

Uranine (Fluorescein disodium salt $\text{C}_{20}\text{H}_{10}\text{Na}_2\text{O}_5$, TCI Inc. New Brunswick, NJ 08901-3605) and oleic acid (Octadecenoic acid, $\text{C}_{18}\text{H}_{34}\text{O}_2$, Spectrum Chemical Manufacturing Corp., Gardena, CA, USA) at a mass (uranine) to volume (oleic acid) ratio of 8.93 were used for making the solutions for $10\text{ }\mu\text{m}$ liquid particles (Faulkner, Smith, and Haglund 2014). An HPLC pump (High Performance Liquid Chromatography, Series 1500, ChromTech, Inc., Apple Valley, MN, USA) was used to transfer the uranine solution to the nozzle of a vibrating orifice aerosol generator (VOAG; model 3450, TSI, Inc., Shoreview, MN, USA) at a constant flow rate (0.225 mL/min). The supplied pressurized air was passed through an air de-humidifier (Model 3Z528, Dayton Electric Mfg. Co., Chicago, IL, USA) and an air dryer to remove moisture. The compressed dry air was mixed with the fine and attached droplets of uranine to separate and disperse the generated liquid particles. The streamline from the nozzle of VOAG was directed to a Krypton-85 Aerosol Neutralizer (Model 54-0024, TSI Inc.) to reduce electrostatic charges between aerosols. The generated aerosols, prior to introduction into the wind tunnel, were analyzed by the aerodynamic particle sizer (APS, Model 3321, TSI, Inc.) to verify the sizes of generated particles. The dried air dispersion and air dilution of the VOAG system was adjusted to generate mainly monodispersed particles. Monodispersed uranine aerosol with an average particle diameter of $10\text{ }\mu\text{m} \pm 1.16\text{ GSD}$ (geometric standard deviation) was generated in the VOAG and analyzed by the APS system.

Correlation between the generated and aerosolized oleic acid particle diameters

Equation (3) (Berglund and Liu, 1973) describes the relationship between the particle diameters (measured by APS) and the parameters used to produce the particles in the wind tunnel.

$$Dp_a = Dp_p \sqrt{\frac{\rho_p}{\rho_w}} \quad (3)$$

Where Dp_a = aerodynamic particle diameter (μm), Dp_p = physical particle diameter (μm), ρ_w = water density = 1 g/cm^3 and ρ_p = particle density = 0.9325 g/cm^3 (dependent on the mass to volume ratio of uranine to oleic acid).

Equation (4) (Berglund and Liu, 1973) shows the calculation of the physical diameter.

Table 1. The shrouded and isokinetic probes tested at different free stream velocities in the study.

Probe Identification	Model A (RF-2-111)			Model B (RF-2-112)		
	RF-2-111 (SUS316L)			RF-2-112 (SUS316L)		
Free Stream Velocity	(10 m/s)	(15 m/s)	(20 m/s)	(5 m/s)	(10 m/s)	(15 m/s)
7.6 mm ISO	27.3 m/s	41.1 m/s	54.2 m/s		41 m/s	27.2 m/s
13.4 mm ISO				42.5 m/s		

$$Dp_p = \left(\frac{6 Q C}{\pi f} \right)^{1/3} \quad (4)$$

Where Q = solution flow rate (ml/s), C = volumetric concentration of aerosol material in the solution (dimensionless), and f = vibrating orifice aerosol generator (VOAG) frequency (Hz).

Verification of the homogenous distribution in the wind tunnel

First the homogenous distribution of the particles in the wind tunnel was verified by two identical 7.6 mm isokinetic probes at 41 m/s free stream velocity. The positions of the two isokinetic probes were interchanged to mitigate any effect of radial aerosol concentration variation that may be present in the wind tunnel flow, and, the same tests were repeated. It was observed that the aerosol concentration differences between the two sampling points, each of which was radially 20 cm apart between the two probes, was typically less than 10% of the average value.

The shrouded probe and the isokinetic probe were mounted side-by-side, 20 cm apart at the exit of the nozzle in the wind tunnel, while the free stream velocity of the wind tunnel was set at 15 m/s. The shrouded probe Model B (RF-2-112) was tested at 57 L/min flow rate. Particles penetrating through each of the probes were collected at the exit of the probes using 47 mm A/D glass fiber filters (Pall Inc., Waltham, MA, USA). The tests were conducted for a fixed time (for the 15 m/s tests for 120 min). A total of five replicate sets were tested. After each set, the inner walls of both probes were thoroughly washed with measured amounts of ethyl alcohol and distilled water and the solutions were analyzed. Similarly, the fluorescein from the filters was also eluted in measured amounts of ethyl alcohol and water and the resulting solutions were analyzed with a Barnstead fluorometer to measure the Fluorescent Intensity Unit (FIU) values (Faulkner, Smith, and Haglund 2014).

LUA sampling in the wind tunnel

The shrouded air sampler (Type A or B) and the isokinetic air sampler with appropriate nozzle sizes were

fitted with 47 mm A/D glass fiber filters (Pall Inc., Ann Arbor, MI, USA). Then they were co-located iso-axially (with 10 cm distances from the cross sections of elliptical duct and the angle of zero degrees relative to the flow) in the wind tunnel, mounted completely horizontally side-by-side (20 cm apart) at the exit of the nozzle, and aligned parallel to each other to collect the LUA uniformly and simultaneously. The free stream velocity of the wind tunnel was set at different speeds of 5, 10, 15 and 20 m/s. The IAS and shrouded air samplers were connected to two separate $\frac{1}{4}$ HP vacuum pumps (Model 0523-V191Q-G588X, Gast Manufacturing Inc., MI, USA) by interface of two separate TSI flow controllers. After the blower run for 5 min, the two pumps were started instantaneously and their flow rates were adjusted according to the calculated numbers for each air sampler.

The homogenous distribution of the particles in the wind tunnel was verified by two identical isokinetic probes. In order to mitigate any effect of radial aerosol concentration variation that may be present in the wind tunnel flow, the positions of the two isokinetic probes were interchanged and the tests were repeated.

After the verification process, 7 different treatments, each with 5 replications were performed in the wind tunnel. The correct operations of the different equipment including the HPLC pump, air dilution, air dispersion, streamline of generated LUA, flowmeters of the shrouded probes and IAS air samplers were monitored periodically during each replicate of different treatments.

Measurement of fluorescent intensity unit (FIU) of oleic acid/uranine particles deposited on filters and inside the walls of isokinetic and shrouded air samplers

After completing each replicate of different experiments, the filter of each air sampler was transferred to a 4 oz./125 mL Nalgene jar with lid (Nalge Nunc International Corporation, Rochester, NY, USA). The remaining particles adhered to the inner wall surface of the isokinetic nozzle and probe of shrouded air samplers were removed with a Kimtech Science Kimwipes 4-1/2" x 8-1/2" delicate task dry wiper

(Kimberly Clark Corp., Irving, TX, USA), and transferred again to small Nalgene jars with lids. The collected filters and delicate task wipers were mixed with 0.01 N NaOH solution, closed, and shaken at room temperature for at least 30 min. Approximately 10 mL of each solution along with blank (pure 0.01 N NaOH) were transferred to a specific test tube and the fluorescein intensity units (FIU) were measured by the calibrated Turner Quantech Digital Filter Fluorometer (Model No. FM109515, Barnstead/Thermolyne Corp., Dubuque, IA, USA). Two filters, NB490 and SC515 were used for primary excitation and secondary emission of the fluorescein solution. In order to measure the standard deviation of the measured FIU values, the reading of each sample (including blank) was repeated three times.

The fluorescein concentration was determined from

$$C = \frac{FV}{tQ} \quad (5)$$

where,

F = fluorometer (Turner Quantech Digital Filter Fluorometer, Model No. FM109515, Barnstead/Thermolyne Corp.), numerical reading,

V = measured solution liquid volume,

t = testing time for each filter, and

Q = aerosol flow rate.

Transmission ratios (TR), aspiration ratios (AR) and wall losses (WL) for both types of probes (shrouded and isokinetic probes) were defined as follows:

$$TR = \frac{C(f, spr)}{C(f, iso) + C(w, iso)} \quad (6)$$

$$AR = \frac{C(f, spr) + C(w, spr)}{C(f, iso) + C(w, iso)} \quad (7)$$

$$WL = \frac{C(w, spr)}{C(f, spr) + C(w, spr)} \quad (8)$$

where,

$C(f)$ = aerosol concentration determined from the filters of shrouded/isokinetic probe.

$C(w)$ = aerosol concentration determined from the wall wash of shrouded/isokinetic probe.

Abbreviations 'spr' and 'iso' were used for shrouded and isokinetic probes, respectively.

Transmission ratio, aspiration ratio and wall losses of both probes were calculated for each particular free stream velocity and particle size. Tests were conducted at free stream mean velocity of 10, 15 and 20 m/s (Model A, RF-2-111) and 5, 10, 15 m/s (Model B, RF-2-112). The particle size tested was 10 μ m AED.

Since liquid particles stretch after entering the APS, and result in biased size measurement, microscopic measurement was applied to evaluate the APS performance for particle size determination. In this case, liquid particles were impacted on cleaned slides coated with NyeBar Type Q (0.2%; Nye Synthetic Lubricants; Fairhaven, MA, USA) and observed under microscope (Faulkner, Smith, and Haglund 2014). Using the flattening coefficient of 1.2 resulted in the particle size of 12.0 μ m for the liquid aerosols generated by the VOAG.

Measurement of fluorescent intensity unit (FIU) of LUA deposited on filters and inside walls of isokinetic and shrouded air samplers

After each test, the vacuum pumps of the (shrouded and IAS) air samplers and the blower of the wind tunnel were stopped, and the air samplers were dismantled carefully. New pairs of gloves and Kimwipes were used to clean the LUA deposited on the outside surface of the air sampler and the inner wall of the shroud tube. Next, new pairs of gloves were used to remove the filters attached to the air samplers and transfer them into two separate Nalgene jars with lids. The wall losses or particles adhered to the inner surfaces of the isokinetic nozzle and the shrouded air samplers were collected by wearing new pair of gloves and using two separate Kimwipes (each one mixed with $\sim$ 1 mL of ethanol). The resulting Kimwipes were transferred again to two separate Nalgene jars with lids.

The collected filters and delicate task wipers were mixed with 20 mL of 0.01 N NaOH solution, closed, and shaken at room temperature and relatively dark area for at least 30 min. Later $\sim$ 10 mL of each solution along with blank (pure 0.01 N NaOH) solution were transferred to a specific test tube and the fluorescein intensity units (FIU) were measured by the calibrated Quantech Digital Filter Fluorometer. The reading of each sample (including blank) was repeated three times. Equation (9) (Chandra and McFarland 1997) was used to calculate the concentration (C values) of LUA deposited on the filters and inner walls of air samplers.

$$C = ((FIU) * V_L) / (Q * t) \quad (9)$$

Where FIU is the fluorometer reading, V_L is the volume of the 0.01 N NaOH solution, Q is the sampling volumetric flow rate, and t is the operation time, for which each test was conducted.

The performance of each shrouded air sampler in comparison with isokinetic was evaluated by the determination of the wall loss (WL), transmission

Table 2. Summary of the shrouded probe Model A (RF-2-111) and Model B (RF-2-112) testing* at all velocities with 10 μm liquid particles.*Model A (RF-2-111) (10 μm)

Free Stream Velocity (m/s)	Transmission Ratio			Aspiration Ratio			Wall Loss Ratio		
	Ratio	SD	95% CI	Ratio	SD	95% CI	Ratio	SD	95% CI
10	0.81	0.05	0.043	0.91	0.06	0.0491	0.10	0.02	0.0213
15	0.95	0.07	0.0631	1.10	0.06	0.0493	0.14	0.03	0.0285
20	1.01	0.05	0.0427	1.31	0.10	0.0838	0.23	0.03	0.0298

*Model B (RF-2-112) (10 μm)

Free Stream Velocity (m/s)	Transmission Ratio			Aspiration Ratio			Wall Loss Ratio		
	Ratio	SD	95% CI	Ratio	SD	95% CI	Ratio	SD	95% CI
5	0.91	0.09	0.0795	0.99	0.10	0.0865	0.08	0.01	0.0083
10	0.94	0.06	0.0541	1.07	0.06	0.0488	0.12	0.02	0.0166
15	1.06	0.07	0.0628	1.26	0.10	0.0877	0.16	0.02	0.0161

*Based on the study of Chandra and McFarland (1997), the flow rate of the shrouded air samplers was maintained at 57 L/min for all of the tests.

ratio (TR) and aspiration ratio (AR) based on Equations (6), (7) and (8) (Chandra 1992).

Results and discussion

Wind tunnel optimization using computational modeling

The verification test showed that the aerosol concentration differences between the two isokinetic sampling points, which were radially 0.10 m away from the center of the elliptical nozzle (about 0.20 m between the two probes), had typically less than 10% deviation from the average value.

Using SOLIDWORKS® Flow Simulation a computational model of the wind tunnel was created in order to find the most optimal configuration and attachments needed to introduce uniform, one-dimensional flow inside. In Figure 2, all four configurations were modeled for the different modifications of the wind tunnel during the experimental process. The initial problem with the original design (Figures 2a and b) originated from the circular mixer impactor (Stairmand plate) causing turbulent vortices in the entrance of the wind tunnel. In Figure 2c, four metal equilateral triangles were installed at the corners of the first segment between the ends of the contraction cone entrance to reduce the vortices generated inside the wind tunnel and prevent the particles from concentrating and adhering to the entrance walls. Although the corner blender parts improved the flow, it still showed vortex concentration issues. When this solution was implemented experimentally, the proper results were still lacking.

In Figure 2d, the Stairmand plate was removed and the wind tunnel model was lengthened. In this configuration a 0.61 m $\times$ 0.61 m $\times$ 1.22 m segment was added in front of the elliptical nozzle that was used to

constrict the air. The removal of the circular mixer impactor in combination of the equilateral triangles allowed the air to flow right through the wind tunnel without getting caught at the impactor plate. The model in Figure 2e shows the final configuration of the wind tunnel. A flow straightener was added between the first two 0.61 m $\times$ 0.61 m $\times$ 1.22 m segments to allow for a more uniform flow once it reached the testing nozzle. The entrance of the wind tunnel was also altered as the ring disk opening with the extended nozzle in the center was replaced with a cylindrical inlet made of sheet metal. This would make the opening of the cylindrical duct the only entry point for the air to enter the wind tunnel. Due to the size of the wind tunnel, the duct diameter was increased and so was the length of the cylindrical entry port. The entry port length was now 0.94 m with a diameter of 0.25 m. These additions increased the air velocity within the wind tunnel, allowing more time for the incoming air to minimize the lateral velocity components caused by the swirling motion and maintain a uniform flow upon entry. The flow Reynolds number for the elliptical entrance to the probe test section ranged from 6.3×10^4 to 2.5×10^5 for the range of velocity conditions tested. The elliptical entrance to the test section has a straight section with a length of 0.94 m such that the velocity profile at the plane of the test nozzle placement is approximately uniform and one-dimensional. The computational fluid dynamic simulation of the wind tunnel flow for nominal air speed of 15 m/s shows approximately uniform velocity profile at the test section (Figure 2e). The results of the computational modeling for the optimized wind tunnel were validated experimentally with the collection of adequate liquid aerosol concentrations that weren't achievable before the wind tunnel configuration was optimized.

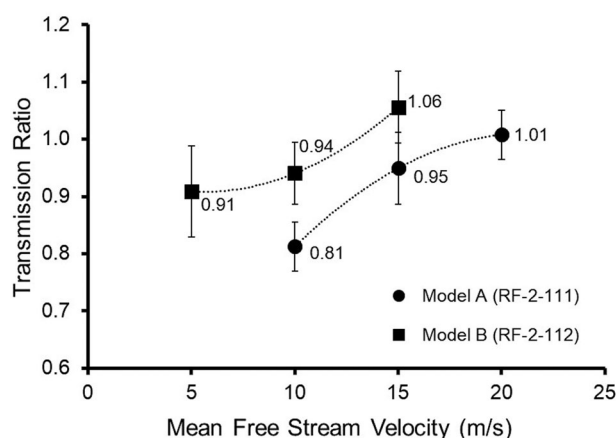


Figure 3. Effects of wind speed on transmission ratio of LUA deposited on the two (Model A and Model B) shrouded air samplers. Each wind speed test was performed with 5 replications.

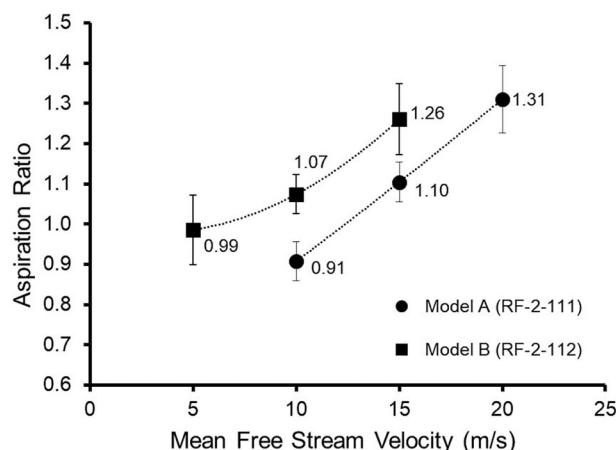


Figure 4. Effects of the wind speed on the aspiration ratios of LUA deposited on two (Model A and Model B) shrouded air samplers. Each wind speed test was performed with 5 replications.

Shrouded probe test results

After the wind tunnel testing, the primary information of each replicate of the different tests with the two types (7.62 or 13.5 mm) of isokinetic and shrouded air samplers were recorded. Table 2 shows the results obtained for the 10 μ m liquid particles in the wind tunnel at the different air speeds (5, 10, 15 and 20 m/s) and various combinations of shrouded and isokinetic air samplers. In order to evaluate the performance of the two types of shrouded probes, the three ratios of wall loss, transmission and aspiration are defined and discussed separately.

The summarized results for the two shrouded probes Model A (RF-2-111) and Model B (RF-2-112) are shown in Table 2 and on Figures 3–5.

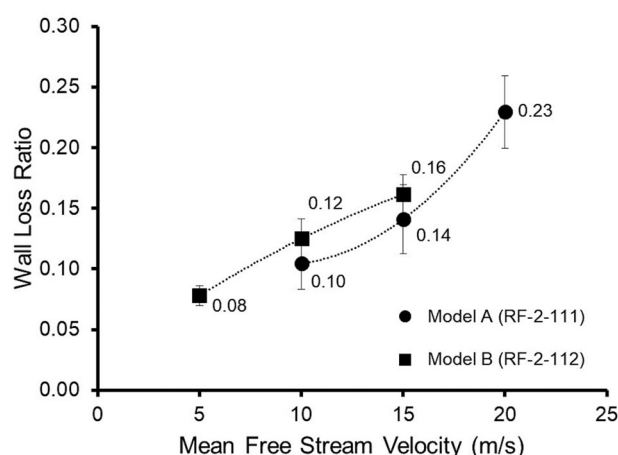


Figure 5. Effects of wind speed on wall loss ratios of LUA deposited on the two (Model A and Model B) probes of the shrouded air samplers. Each wind speed test was performed with 5 replications.

Transmission ratio (TR)

Equation (6) was used to calculate the transmission ratios for the different combinations of the shrouded and isokinetic air samplers. Table 2 shows the performance of the two (A and B) shrouded probes in combination with appropriate isokinetic air samplers at 5, 10, 15 and 20 m/s velocities in terms of transmission ratios. Furthermore, these tables also show that the standard deviations and COVs (Coefficient of Variation) of resulting transmission ratios for shrouded probes of B and A were less than the expected value of 10% regardless of the type of the shrouded probe tested in combination with the isokinetic air sampler. When the air speed in the wind tunnel for the shrouded probe A or B, respectively, was increased by a factor of two (from 10 to 20 m/s) and by a factor of 3 (from 5 to 15 m/s), their related transmission ratios respectively increased 24.7% (from 0.81 to 1.01) and 16.5% (from 0.91 to 1.06) (Figure 3). Additionally, the B probe (low flow model) had 16.1% (at 10 m/s) and 11.6% (at 15 m/s) higher TR than the probe of A (high flow model).

The transmission ratios using the 10 μ m LUA for the shrouded probes tested in this study were consistent with the guidelines of ANSI/HPS N13.1 (1999/2011) and with the performance of these probes studied by Chandra and McFarland (1997). According to ANSI/HPS N13.1 (1999/2011), the aerosol transmission ratio of shrouded air samplers should be in the range of 0.80 to 1.30.

Aspiration ratio (AR)

Aspiration ratio or aspiration efficiency was calculated to quantify the bias in the aerosol concentration

entering the inlet of probe in shrouded air samplers. In other words, AR is defined as the ratio of aerosol concentration drawn (by suction) from the airstream in the wind tunnel into the inside of probe to the bulk aerosol concentration of the air stream (Sippola and Nazaroff 2014). Table 2 shows the performance of two (A and B) shrouded probes in combination with appropriate isokinetic air samplers at 5, 10, 15 and 20 m/s in terms of aspiration ratios. Furthermore, these tables also show that the standard deviations and COVs of the resulting aspiration ratios for shrouded probes of A and B were less or equal to the expected value of 10% regardless of the type of shrouded probe tested in combination with the isokinetic air sampler. When the air speed in the wind tunnel with the shrouded probe A or B respectively increased by a factor of 2 (from 10 to 20 m/s) and by a factor of 3 (from 5 to 15 m/s), their related aspiration ratios respectively increased 44% (from 0.91 to 1.31) and 27.3% (from 0.99 to 1.26) (Figure 4). In fact, the Model B shrouded probe had 17.6% (at 10 m/s) and 14.6% (at 15 m/s) higher aspiration ratios compared to Model A at similar airstreams. The aspiration ratios for both Model A and Model B follow the ANSI/HPS N13.1 (1999/2011) requirements of 0.80 to 1.50.

Wall loss ratio

The wall loss (WL) ratio in a probe of shrouded air sampler is the ratio of the equivalent aerosol concentration deposited on the internal walls of the probe to the aerosol concentration at the probe entrance plane (McFarland and Rodgers 1993). Based on the measured FIU data and applying Equation (8), the concentration of LUA in the wall losses of the shrouded and isokinetic air samplers at different combinations was calculated for each replicate of the different treatments. Table 2 shows the wall loss ratios of two (A and B) shrouded probes in combination with appropriate isokinetic air samplers at different wind speeds of 5, 10, 15 and 20 m/s. Furthermore, the resulting COV values for the wall loss ratios for the shrouded probes of A and B were higher than the expected value (10%), and respectively increased to 23% and 15% at the wind speed of 10 m/s. When the air speed in the wind tunnel increased by a factor of 2 (from 10 to 20 m/s) for the Model A shrouded probe and by a factor of 3 (from 5 to 15 m/s) for the Model B shrouded probe, their related wall loss ratios respectively increased by 130% (from 0.10 to 0.23) and by 100% (from 0.08 to 0.16) (Figure 5). These results

show that the type B shrouded probe (with larger and constant cross-section diameter (34.81 mm) had less wall loss ratio than type A with smaller cross section (18.5 mm). This situation was reversed at constant wind speed. The type B had 20% (at 10 m/s) and 14.3% (at 15 m/s) higher wall loss ratios than the Model A shrouded probe (Figure 5). However, the average wall loss ratios for both shrouded probes were in acceptable ranges (ANSI/HPS N13.1 1999/2011).

The wall loss ratios for the 10 μ m particles measured for Model A were 10.5% and 23% at the airspeeds of 10-20 m/s and for the Model B shrouded probes the ratios were between 7.8% and 16.2% at the air velocity of 5-15 m/s (Figure 5).

Based on the t-tests that were performed for the Model A and Model B data with the 10 m/s and 15 m/s velocities that overlap for both probes, the “15 m/s Aspiration Ratio,” “10 m/s Transmission Ratio,” and “10 m/s Aspiration Ratio” had a significant statistical difference with a *p*-value less than 0.05. There was no statistical difference between the wall loss ratios for Model A and Model B at the overlapping 10 m/s or 15 m/s airspeed.

Future research will focus on designing new shrouded probes to minimize wall losses and compare their performances with similar shrouded probes for air sampling. The wind tunnel will be modified to improve the uniform, one-dimensional flow pattern and reduce the wall losses. The COV of the concentration profiles of aerosol particles at the center two-thirds of the duct cross-sectional area will be monitored to ensure that it does not exceed 10%. In addition, the turbulence intensity will be studied in the test section within the center two-thirds of the duct cross-sectional area.

Conclusions

The two shrouded probes of Model A (RF-2-111) and Model B (RF-2-112) achieved reasonably good results in terms of wall loss, transmission and aspiration ratios based on the collection of 10 μ m monodispersed LUA at relatively high concentration, steady state (constant) flow wind speeds, and zero angle between the free airstream and nozzle entrance. However, the two types of shrouded air samplers had different ratios. While Model B had higher transmission and aspiration ratios than Model A showing a significant statistical difference for the 15 m/s Aspiration Ratio and 10 m/s Transmission Ratio, it had a higher wall loss ratio than Model A. However, there was no statistical difference between the wall loss ratios for Model

A and Model B at the overlapping 10 m/s or 15 m/s air velocity.

The differences in performance could be explained by the different geometries of the two shrouded probes. The inner probe in Model A has a smaller inlet diameter compared to that in Model B (18.5 mm versus 34.81 mm). Model A has higher Stokes number, indicating higher inertial effect, with higher divergence in the nozzle that increases the likelihood for wall losses. The higher Stokes number and greater expansion ratio from shrouded nozzle inlet to nozzle exit result in lower transmission and aspiration ratios in Model A (Fran et al. 1992).

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